A Sustainable Business Model – Sustainability Accounting

Innovation Report

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Abstract

Business efficiency, stakeholder pressure and the need for legislative compliance compel the automotive sector to design and manufacture low-impact, environmentally responsible and sustainable vehicles. Managing and responding to these multiple and sometimes conflicting interests requires the measurement of economic, environmental and societal performance. This Innovation Report describes the process of developing the automotive Full Cost Accounting (FCA) model to drive sustainable decision-making in the automotive sector. FCA exhibit appealing advantages in comparison with other sustainability assessment techniques, with the most important one being the ability to support decisions by translating a broad range of conflicting sustainability information into the widely known and acceptable business language of 'money'.

A systematic and rigorous literature review of over 4300 papers related to FCA extracted ten FCA methods with a diverse level of completeness and consistency in practical applications. The critical analysis of each approach and existing automotive sustainability measures indicated the Sustainability Assessment Model (SAM) as potentially the most complete FCA method applicable in automotive organisations. A new set of assessment criteria has been developed to adapt the SAM to the automotive setting by: (1) selecting a set of sustainability assessment criteria from the literature, (2) refining these through an interview study with 24 experts in the automotive industry. By adapting this expert-driven approach, 26 midpoint and 9 end-point economic, environmental, resource and social impact categories have been identified for the construction of a comprehensive and novel framework for automotive sustainability assessment. This Engineering Doctorate project has complemented this framework with valuation models for resource depletion impacts, while valuation models for another ten impacts, including global warming potential, photochemical ozone creation potential, acidification potential, particulate matter formation, eutrophication potential, water consumption, land use, mobility capability, employment (quantity) and occupational health and safety, have been supplied by the consulting company PricewaterhouseCooper (PwC).

This Engineering Doctorate, with the assistance of PwC, has developed and proved with real world data an innovative model that will enable large car manufacturers to evaluate options, identify win-wins and optimise trade-off for complex and multi-disciplinary sustainable decisions. The Automotive SAM (A-SAM) measures and quantifies a broad range of economic, environmental, resource and social impacts caused by the automotive sector. By adapting a rigorous and robust approach, it translates these impacts into their monetary equivalents, which is a language and thinking that could be understood in different business areas and by different stakeholders. It enables managers and design engineers in the automotive sector to develop a better understanding of the environmental, resource and social impacts of their activities, products, processes and materials used, while still ensuring cost-effectiveness when making decisions. It can expose new business or investment opportunities for automotive organisations, in line with the principles of sustainable development, by making them more transparent and visible for decision-makers.

Declaration

This innovation report is submitted to the University of Warwick in support of my application for the degree of Engineering Doctorate. It has been composed by myself and has not been submitted in any previous application for any degree. The work presented (including data generated and data analysis) was carried out by the author.

Engineering Doctorate Mentors

Academic Mentors: Professor Kerry Kirwan, Dr James Meredith
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Abbreviations

A-SAM	Automotive Sustainability Assessment Model
BSS	Balanced Scorecard for Sustainability
CBA	Cost Benefit Analysis
EIA	Environmental Impact Assessment
ELECTRE	ELimination and Choice Expressing REality
E P&LA	Environmental Profit and Loss Account
FCA	Full Cost Accounting
FCVs	Fuel Cell Vehicles
FFF	Forum for the Future
GRI	Global Reporting Initiative
GWP	Global Warming Potential
HDVs	Heavy-Duty Vehicles
HEVs	Hybrid Electric Vehicles
HVs	Hybrid Vehicles
IPA	Impact Pathway Analysis
IRIS	Interactive Robustness analysis and parameters' Inference for multi-criteria Sorting problems
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LDVs	Light-Duty Vehicles
MCDA	Multi-criteria Decision Analysis
MDVs	Medium-Duty Vehicles
MFCA	Material Flow Cost Accounting
PGE	Platinum Group Element
PGMs	Platinum Group Metals
PHEV	Plug-in Hybrid Electric Vehicles
PwC	PricewaterhouseCoopers
SAM	Sustainability Assessment Model
SBM	Sustainable Business Model
SCP	Surplus Cost Potential
SMAA-TRI	Stochastic Multicriteria Acceptability Analysis for ELECTRE TRI
SV	Sustainability Value
TIMM	Total Impact Measurement and Management

1. Introduction

In the last half century, cars have become an important part of our lives and provide personal mobility with speed, comfort and convenience. However, the car-based transport has also brought a wide range of environmental and social impacts, for example, the depletion of natural resources, contribution to global warming, acidification of the atmosphere, congestion, accidents and noise. Nowadays, stakeholders are more anxious about these social and environmental issues and expect automotive organisations to consider them in their operations and decision-making.

For example, governments encourage businesses to support social and environmental initiatives through new legislation, regulations and taxes. Financial investors show interest in assessing organisational sustainability performance to determine any potentially negative risk factors. Businesses also have a responsibility to shareholders who expect financial returns. One way to manage and respond to these multiple and sometimes conflicting interests is the development of new and Sustainable Business Models (SBMs), the aim of which is to find a balance between long-term ‘profitability and productivity’ and ‘environmental and social impacts’.

1.1. The need for this project

SBMs can be applied to all business areas in order to drive sustainable decision making. This represents a key challenge for manufacturing activities where decisions are often made based on economic rationale rather than other influences that may impact on total value. Jaguar Land Rover (JLR), a British automotive company and the sponsor of this project, has recognised that sustainability-related business model innovation requires the measurement and assessment of economic, environmental and societal impact and values. When this Triple Bottom Line (TBL) approach is applied there may be alternative products or services which present an overall higher value or longer-term sustainability.

JLR does not have an appropriate system that allows it to capture, monitor and communicate TBL performance at the wider all-function level (see Figure 1). Corporately, JLR measures and reports their sustainability performance using a widely accepted reporting framework, the Global Reporting Initiative (GRI). However, the GRI framework reports sustainability performance primarily for the company as a whole rather than for individual products, projects, processes or materials.

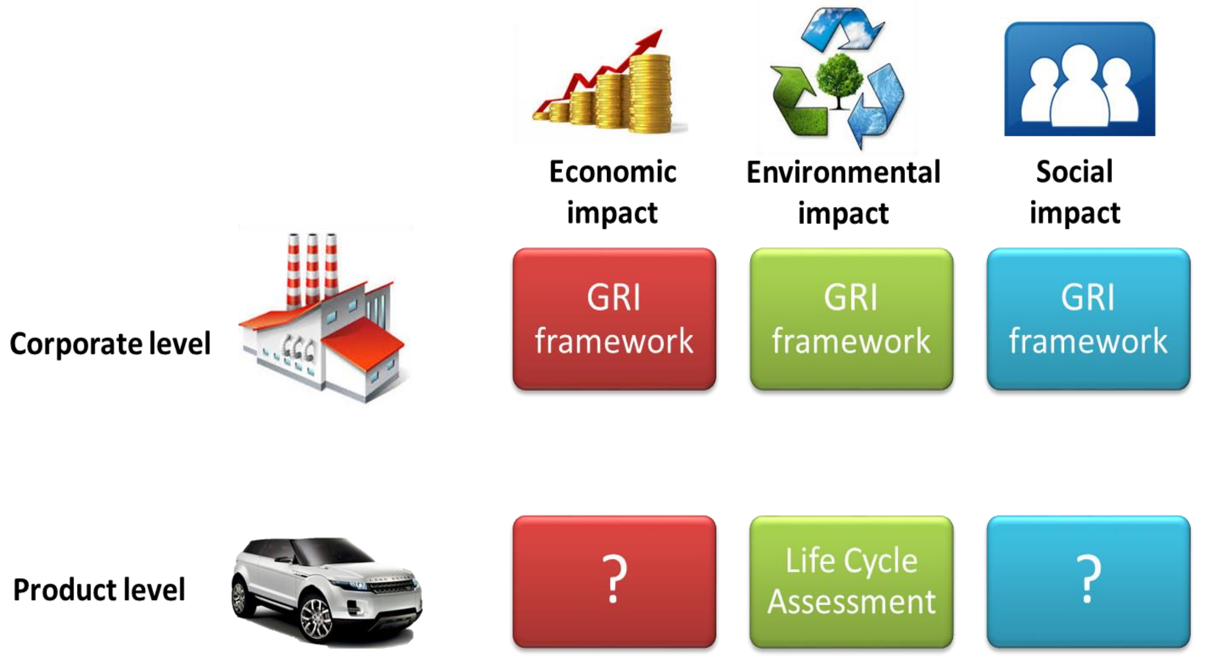

Fig. 1 JLR’s performance measurement system for sustainability

At the product level, sustainability assessment is limited exclusively to a life cycle assessment (LCA) technique which measures the impacts of raw material use, production, customer exploitation and disposal. LCA is a well-established and standardised method widely used in the automotive sector; however, it concerns only environmental assessment whilst the economic and social attributes of a vehicle are ignored.

In order to make the best possible choices, design engineers and managers in the automotive industry need effective and credible measurement tools to understand all of the economic, social and environmental impacts of their decisions as early in the product design cycle as possible (Fiksel, 2009). Vehicle design and development is considered to be the most important stage of the automobile life cycle because it determines the lifetime costs and overall sustainability performance such as fuel consumption, materials composition, safety and emissions (MacLean and Lave, 2003). The decisions made at this point have economic, environmental and social implications throughout the entire lifetime of the vehicle, which LCA alone cannot determine and account for. Hence, automotive organisations need complementary tools to LCA in order to support more informed decisions and get a complete assessment of sustainability performance, which served as the basis of this Engineering Doctorate (EngD) research project.

1.2. Research objectives

The aim of this project was to provide the sponsor company, JLR, with an integrated, holistic and comprehensive model for automotive sustainability assessment to drive sustainable decision-making. A Full Cost Accounting (FCA) concept, classified under the umbrella of sustainability accounting tools, was selected as a structure to define such a model. FCA was designed to adjust the existing prices of products and services by monetising and incorporating into the equation both internal and external impacts (positive and negative), including environmental and social externalities (Bebbington et al., 2001).

FCA is a potentially attractive option to support business decision-making due to its ability to capture more than just financial values and embrace both internal and external sustainability impacts (Bebbington et al., 2001, Russell, 2011). The designers and managers in the automotive organisation make several thousand decisions every year and that thousands of people are involved. Hence, it became critical to implement everyday language and thinking that could be understood in different business areas. FCA translates a range of conflicting sustainability information into a monetary unit score which is an effective way of communicating trade-offs, win-wins and outcomes for complex and multi-disciplinary sustainability decisions.

More specific reasons why FCA was favoured over other sustainability assessment technologies will be presented in Section 2.

In order to achieve the research aim, a series of intermediate objectives were identified, and these include:

- **To identify FCA methods that have been developed to date and select the most appropriate method for the automotive setting;**
- **To adapt the FCA method for the automotive industry by developing a comprehensive set of assessment criteria for automotive sustainability assessment;**
- **To develop a valuation model for environmental and social risks and impacts; and**
- **To test the developed model based on 'real world' input data.**

Each of these objectives have been addressed in research reports and submissions which together form the portfolio for this Engineering Doctorate.

It is important to note that this project does not propose a complete FCA solution for the automotive sector, from start to finish. Instead, it assesses the current state of the art in FCA methods, defines gaps and weaknesses in this area, and then develops novel capability to fill the identified gaps and weaknesses.

1.3. Structure of this report and EngD portfolio

Section 1 has discussed the motivation for this EngD project. Section 2 introduces the reader to the subject area by reviewing the latest SBM literature and justifying the reasons for selecting the FCA approach over other sustainability assessment systems. Section 3 is a systematic literature review of over 4300 papers conducted in order to identify the state of the art in FCA and select the one that best fits the specifications and needs of an automotive business. Section 4 describes the processes and methods used to adapt the FCA method to the automotive setting by developing a framework for automotive sustainability assessment. Section 5 describes the valuation methods for environmental and social impacts considered in the automotive FCA model, with resource depletion impacts being identified as the highest-priority areas in this work. Section 6 develops a comprehensive approach to resource depletion impact assessment and tests the approach based on a set of sample materials used in automotive manufacturing. Section 7 discusses the main research outcomes and limitations of the work. Finally, the main conclusions of the project, including the project impact and suggestions for future work, are summarised in Section 8.

This EngD research contains five main submissions and one supplementary submission. Figure 2 illustrates the structure of this Innovation Report and where in this document the portfolio submissions are covered.

All publications resulting from this research, the author's personal profile, international placement report, and post-module assignments are submitted in addition to this portfolio and can be read independently of the main submissions.

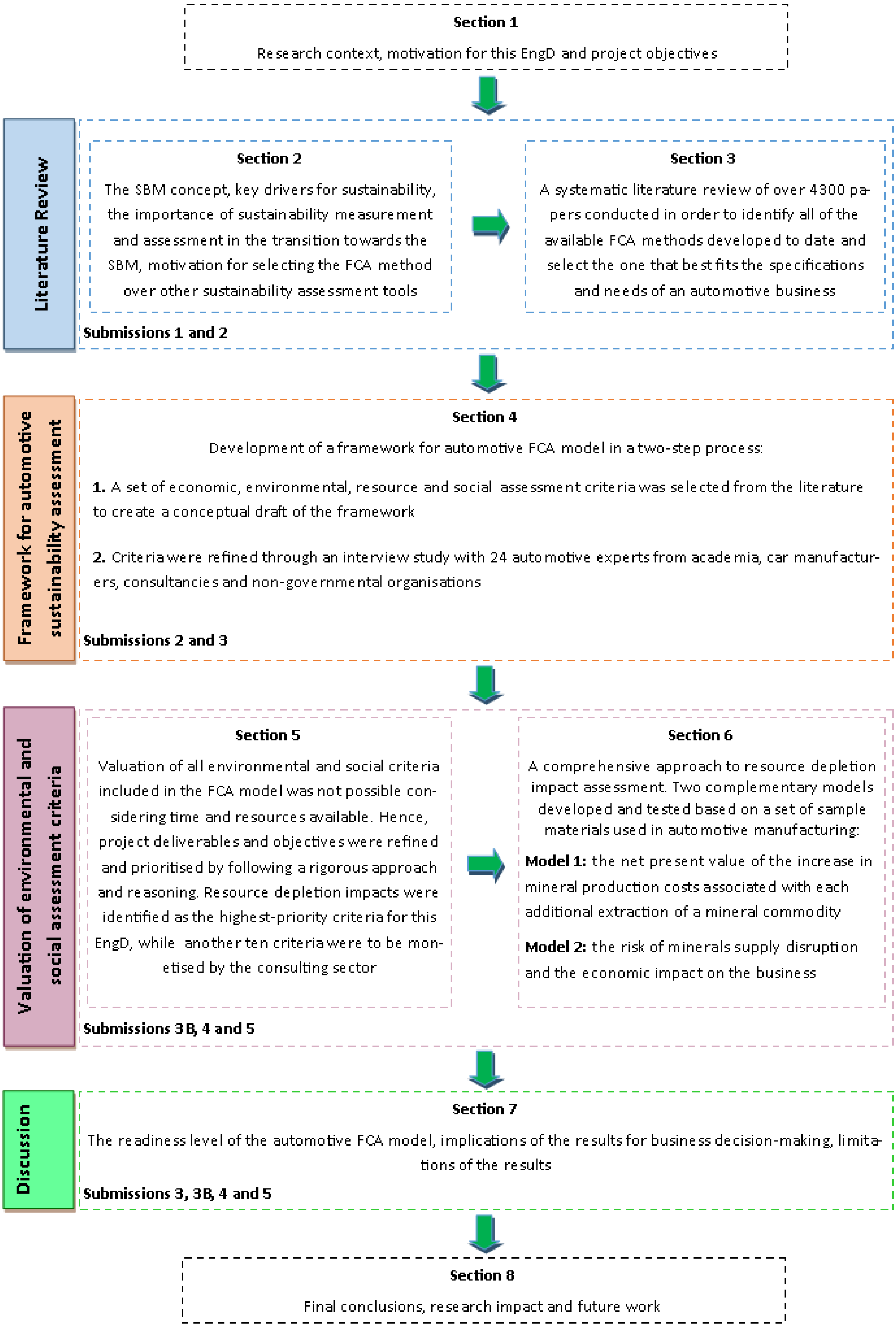

Fig. 2 Structure of this Innovation Report and correlation of portfolio submissions with individual chapters

2. Research background

This section introduces the reader to the subject area and by reviewing the latest SBM literature. Motivation for selecting the FCA method over other sustainability assessment tools is also explained.

2.1. The concept of a sustainable business model

By linking the business model and sustainability theories, a general understanding of the SBM concept was developed. A business model represents a company's core logic and the strategic choices it makes to create, deliver and capture value within a value network (Shafer et al., 2005). The TBL theory of sustainability considers value in three major dimensions: economic, environmental and social (Elkington, 1997). Hence, the SBM imposes on organisations the responsibility to focus not just on the economic value they add but also on the environmental and social value they either add or destroy (Khalili, 2011).

The core problem of this general interpretation of the SBM is that organisations do not operate in a vacuum. They form part of a larger socio-economic system in which they interact with different stakeholders, including the natural environment (see Figure 3) (Stubbs and Cocklin, 2008). The SBM moves beyond the transformation of a company's internal business processes, practices and policies. The whole socio-economic environment needs to contribute to global sustainability development (Morioka et al., 2016). A sustainable organisation cannot operate in an unsustainable economy (Howes, 2002).

Transforming the global economy towards sustainable development is a very long-term process that requires the concerted action of all stakeholders in, for example, promoting and switching consumption to sustainable products, the transformation of taxation and accounting systems, the development of long-term sustainable value chain systems or investing in infrastructure for a sustainable system (Stubbs and Cocklin, 2008). Transitioning the world onto a sustainable consumption and production trajectory is likely to take years if not decades. The International Energy Agency (IEA) predicts that although electric and fuel cell vehicles (FCVs) will most likely be dominant by 2050, people will still be using internal combustion engines to power their cars (Tanaka, 2011). For this reason, the SBM should not be considered a goal or complete solution; rather it is a process of constant commitment, innovation and improvement (Kerr, 2006, Jørgensen, 2008, Kiron et al., 2013).

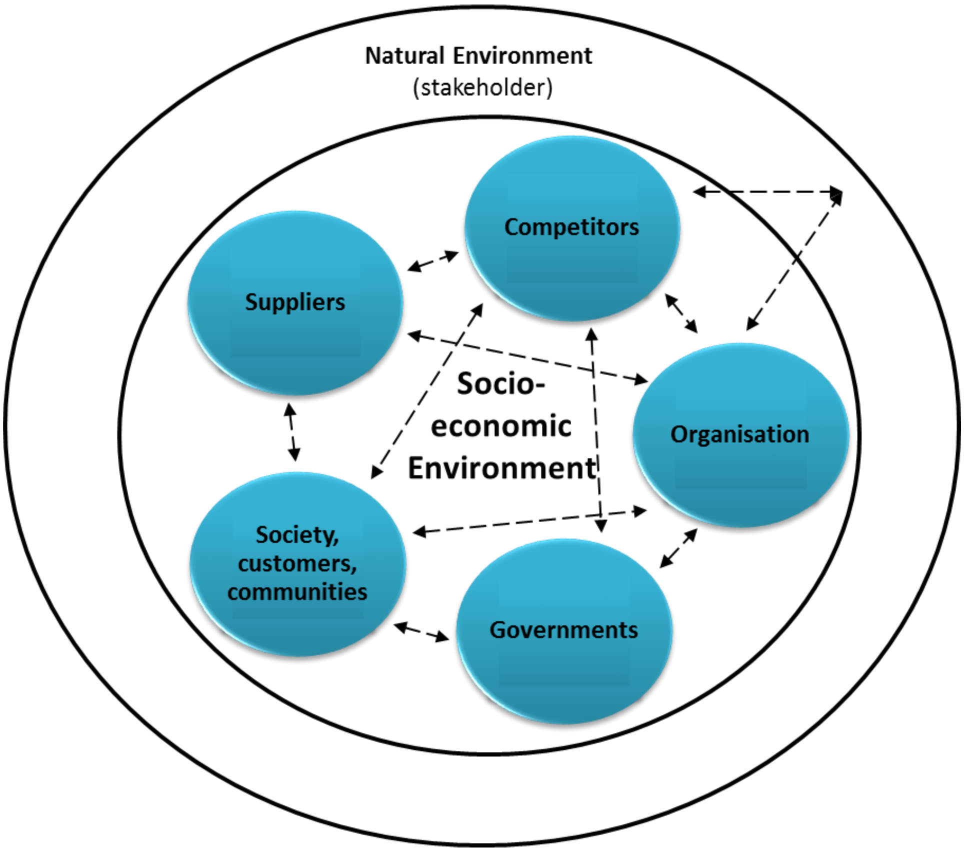

Fig. 3 The socio-economic environment and key stakeholders of an organisation, with arrows representing interactions between stakeholders (adapted from: Stubbs and Cocklin, 2008)

Ongoing improvement and learning should be part of any organisation's life and is central to many popular schools of management such as Business Process Reengineering (BPR), Lean management or Total Quality Management (TQM) (Bond, 1999, Koenigsaecker, 2013). In fact, global sustainability leaders borrow principles and tools from the TQM and Lean management schools. For example, Interface Inc. built its sustainability strategy based on the foundations of Lean theory. The company began its sustainability improvement process in 1994 (Gustashaw and Hall, 2008) and continues to develop it today (Interface Inc., 2015).

2.2. Key drivers for business sustainability

The survey of relevant literature and corporate sustainability best practice (e.g. Khalili, 2011, Eccles et al., 2012, Hall and Wagner, 2012, Kiron et al., 2013) suggested six key drivers/enablers of business change for sustainability, as outlined in Figure 4 below.

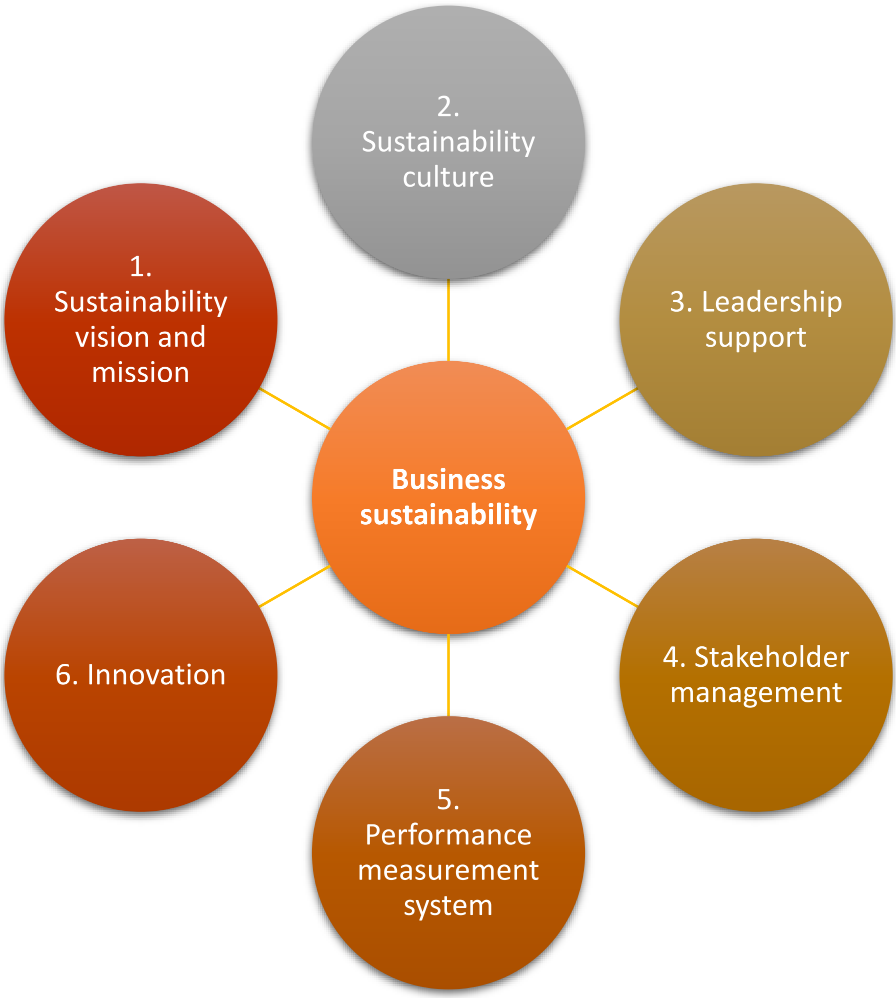

Fig. 4 Six key drivers of business sustainability

- **Sustainability vision and mission** – Sustainability has to be approached in the same way as any other business idea or influence. Hence, companies need to consider sustainability during the strategic planning process and incorporate it into their business strategy and goals. Only then can it be implemented appropriately across an organisation through business models, roadmaps or operational plans (Khalili, 2011).
- **Sustainability culture** – Sustainability has to be an element of a company's culture in order to influence all people in an organisation. It should provide opportunities and implications for all business activities, including the design of new products (services), manufacturing processes, the building of new facilities and even supplying offices (Ayman and Hartman, 2011). Sustainability needs to become part of people's everyday conversations, thinking and the fabric of doing their job (Kiron et al., 2013).
- **Leadership support** – Embedding sustainability in an organisation's culture requires strong commitment and support from executives. They hold the power to effect change and ensure sustainability opportunities are placed front and centre (Eccles et al., 2012, Kiron et al., 2013). Interface Inc.'s commitment to sustainability was initiated by its CEO. Only sustainability leaders have the ability to create a culture of sustainability and embed these values in the minds of key stakeholders (Stubbs and Cocklin, 2008).
- **Stakeholder management** – Any transition towards sustainability needs to be carried out in collaboration with stakeholders. A company has to identify and manage stakeholders' needs and expectations. Managers do not always recognise all organisational impacts on the environment and society (Taplin et al., 2006). Collaboration with stakeholders can draw attention to issues not previously raised and identify credible, meaningful and feasible sustainability objectives that go beyond appearing as marketing spin (Kiron et al., 2013).
- **Performance measurement system** – The popular maxim of management guru Peter

Drucker – ***what cannot be measured cannot be managed*** – is also relevant for business sustainability. Sustainability decisions cannot be reduced to an exclusively economic rationale. Instead, they should evaluate and consider other influences that may affect the total value (e.g. human, social, natural and intellectual capital) (The International Integrated Reporting Council (IIRC), 2013). Any business striving for sustainability should be equipped with some form of algorithm, indicator or financial mechanism that will incorporate these other influences into its everyday decision-making (Lüdeke-Freund, 2010).

- **Innovation** – A transition towards sustainability is about doing things differently and doing different things (Kiron et al., 2013). This requires completely new thinking about the discovery and development of new products, technologies, production processes and institutional and systemic arrangements as well as existing business models (Van der Heijden, 2011, Boons and Lüdeke-Freund, 2013).

All of these sustainability drivers are essential for creating capabilities for change and supporting the implementation of sustainability. However, robust and innovative business models for sustainability cannot exist without an appropriate system of performance measurement (Lüdeke-Freund, 2010, Sherman, 2012, Boons and Lüdeke-Freund, 2013). It is true that a company becomes what it actually measures (Hauser and Katz, 1998). A performance measurement system is an indispensable element of any change and management process (Sherman, 2012). The Lean, TQM and Six Sigma concepts confirm that continuous improvement is about the constant measurement and improvement of organisational performance (Fryer et al., 2007, Koenigsaecker, 2013).

These findings have cast a new light on this research and exposed new opportunities to advance this EngD project. Since the SBM is the continuous process of making strategic and operational decisions about appropriate strategies, technologies, practices or activities, managers in the automotive industry need measurement tools and models that will support them in making the best possible decisions. With JLR still lacking an appropriate measurement system that allows it to capture, monitor and communicate sustainability performance at the wider all-function level (see Figure 1), the development of such a system served as the basis of this EngD research project. Various models for assessing sustainability exist in the wider literature (see Ness et al., 2007, Singh et al., 2009, Poveda and Lipsett, 2011), each of which has its own strengths and limitations. The next section evaluates these models and selects potentially the most attractive one to support automotive internal decision-making.

2.3. Sustainability assessment technologies

A versatile and ideal tool or method to assess sustainability is difficult, if not impossible to establish, since every evaluation differs in terms of a specific goal, focus, type of data and needs of stakeholders. Hence, the appropriateness of sustainability assessment methods for automotive decision-making was evaluated by considering the characteristics and needs of the automotive sector reported in the literature (Steen, 1999, Schmidt and Taylor, 2006, Mayyas et al., 2012, Arena et al., 2013, Jasinski et al., 2015), followed by consultations with the sponsoring company. By adopting this approach, the following four design attributes for the automotive sustainability assessment system were defined:

- **Attribute 1:** the system should capture both internal (e.g. the use of energy, materials and water, and waste generation) and external sustainability impacts (Steen, 1999, Arena et al., 2013). External impacts are the damages or negative effects of an entity's activities and decisions borne elsewhere in the system by parties not responsible for causing the effects in the first place (e.g. various forms of air, water and soil pollution) (Russell, 2011). As with carbon dioxide, externalities can be internalised at a certain point in time and are therefore considered as future costs.

- **Attribute 2:** existing automotive sustainability assessment techniques demonstrate that life cycle thinking is deeply ingrained in the automotive industry (see Steen, 1999, Schmidt and Taylor, 2006, Arena et al., 2013). Automobiles have extensive ecological and social impacts (e.g. energy consumption, contribution to global warming, waste, noise and accidents) at every stage of their life cycle (Mayyas et al., 2012). Hence, car manufacturers are under pressure from policymakers and other stakeholders to measure and improve both the direct and indirect (upstream and downstream) sustainability performance of vehicles (Jasinski et al., 2015).
- **Attribute 3:** based on TBL theory, all three sustainability dimensions strongly influence each other and should be an integral part of the business's decision to pursue sustainable development (Elkington, 1997).
- **Attribute 4:** design engineers and managers in the automotive business need to formulate some kind of mathematical function to assess all conflicting objectives before making decisions (Mayyas et al., 2013). Despite heavy criticism in the literature (see Schmidt and Sullivan, 2002, Jasinski et al., 2015), monetisation is an effective weighting method that enables a range of conflicting information to be translated into a single monetary unit score (Steen, 1999). For example, 1 kg of carbon dioxide creates a different severity of social and environmental impact than 1 kg of nitrogen oxides. Once converted into monetary units, these impacts are conceivable and their importance can be directly and intuitively grasped by different areas of the business (Bickel and Friedrich, 2005).

During the European Union (EU) project named "Sustainability-A" around 50 tools considered appropriate for sustainability assessment were categorised in 7 groups (De Ridder et al., 2007, Lotze-Campen, 2007): (1) assessment frameworks, (2) participatory tools, (3) scenario tools, (4) sustainability accounting tools, (5) physical analysis tools and indicator sets, (6) model tools and (7) Multi-Criteria Decision Analysis (MCDA). Amongst these seven groups of sustainability assessment methods, only sustainability accounting, also known as Environmental Management Accounting (EMA), tools have the ability to provide monetised sustainability information.

The purpose of EMA is to assist the internal planning and decision-making process within an organisation by measuring environmental information and making it more visible for decision-makers (Schaltegger and Burritt, 2000). EMA identifies, collects and analyses both physical information (e.g. use and flows of materials, energy, water and waste) and monetary information on environment-related earnings, costs and savings (Burritt et al., 2002, Jasch and Savage, 2009). EMA encompasses the following five principal tools and systems: Life-Cycle Costing (LCC), Full Cost Accounting (FCA), Cost-Benefit Analysis (CBA), Balanced Scorecard for Sustainability F(BSS) and Material Flow Cost Accounting (MFCA) (Jasch and Savage, 2009, Qian and Burritt, 2009). Figure 5 assesses these five EMA tools against previously defined design attributes for the automotive sustainability assessment system.

Out of five EMA technologies, only the FCA method met all four attributes, and thereby was potentially an attractive option to form a system for automotive sustainability assessment. Background information about FCA is provided in **Submission 2** and Jasinski et al. (2015). An important methodological note is that FCA utilises LCA as a means to generate input data, which can then be converted into monetary values (Bebbington et al., 2001). The advantage of this approach is that most automotive organisations, including JLR, report their sustainability performance in LCA format, thus they already have well-developed LCA capabilities. Integrating FCA with LCA technologies gives a scientific background to the assessment by following the widely accepted ISO 14040 standards.

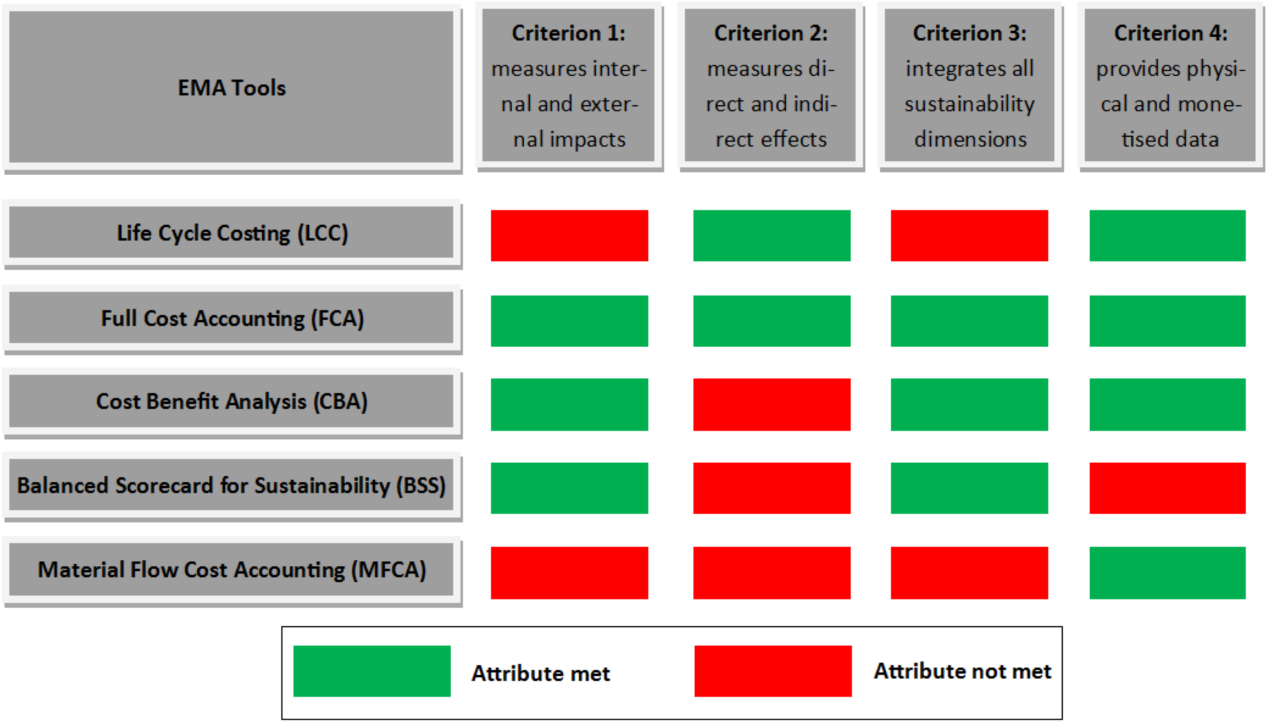

Fig. 5 A comparison of EMA tools against the design attributes defined for the automotive sustainability assessment system

FCA is not a new concept with a number of methods developed to date and applications in many different settings such as the chemical industry (Taplin et al., 2006), oil and gas industry (Bebbington, 2007), urban development (Xing et al., 2009) and sportswear industry (PUMA, 2010). In order to assess its potential in the automotive context, the aims of **Submission 2** were to review and identify existing FCA methods and select the most appropriate approach for the automotive sector. This will be discussed in the forthcoming sections of this Innovation Report.

3. Selection of the most suitable FCA method

A systematic literature review of 4381 papers has been conducted in order to identify all available FCA methods developed to date and select the one that fits the specifications and needs of an automotive business. A systematic review aims to bring together all known knowledge on the given topic area by systematic, exhaustive and comprehensive searching, appraising and synthesising research evidence (Grant and Booth, 2009). The advantages of this approach over the conventional review, which lacks an explicit intent to maximise scope or analyse data and therefore is open to bias by not questioning the validity of statements made, potentially omitting significant sections of the literature or by selecting literature that represents a specific world view (Grant and Booth, 2009), are objectivity, transparency, minimised risk of bias in the results, and its methodological and standardised approach (Denyer and Tranfield, 2009, Booth et al., 2011, Jesson et al., 2011). A systematic review of FCA methods was not available in the literature and it was needed to identify all the methods that have been developed to date.

The review process followed a review protocol, shown in Table 1 that contains information about the review question, inclusion criteria, search strategy, data extraction, quality assessment and data synthesis (Petticrew and Roberts, 2008, Tacconelli, 2010, Booth et al., 2011). Diversity and heterogeneity of the FCA literature required a combination of different techniques at different stages of the review process.

The primary publications included in the review process were full papers in peer-reviewed journals. However, a systematic review should include all relevant studies regardless of publication status in order to avoid publication bias (Centre for Reviews and Dissemination (CRD), 2009). A vast quantity of FCA evidence exists in grey literature (e.g. government publications, conference papers, research, business or industrial reports). As such, a wide range of published and unpublished studies were accepted in the review process, excluding presentations, book reviews and comments.

Table 1 Review protocol designed for the literature review process

Step	Research question/Methods
Review question	What FCA methods have been developed to date?
Inclusion criteria	**Population:** Studies representing the FCA concept **Intervention:** No intervention in the research question **Comparison:** No comparison in the research question **Outcome:** Studies that represent, constitute or strengthen any FCA method
Exclusion criteria	Presentations, book reviews, comments and all studies reported in a language other than English
Searching the literature	**Methods:** database searching, grey literature searching, reference list checking, citation searching and consultation with an expert **Databases searched:** Google Scholar, ScienceDirect, Emerald Insight, Wiley Online, Web of Science **Keywords for database searching:** 'full cost accounting', 'total cost accounting', 'full environmental cost accounting', 'total cost assessment' and a combination of the following terms: 'accounting', 'valuing', 'externalities', 'external cost', 'social accounts' and 'environmental accounts'
Quality assessment	**Methods:** hierarchy of study design (experimental, observational, expert opinion) and quality checklist (lists of questions appropriate to the research question)
Data extraction	**Data extraction form with categories developed from relevant studies:** title, authors, year of publication, place of study, type of industry, type of focus (industry, organisation, project, product or process) and a brief description of the methodology used **Software used for extracting data:** Microsoft Access
Data synthesis	**Methods:** narrative synthesis, categories developed from a detailed examination of all FCA studies **Presentation methods:** tables, matrices and qualitative thematic analysis

The review included only studies reported in English because the majority of FCA studies have been conducted in native English-speaking countries (such as the United Kingdom

(UK), New Zealand, the United States of America (USA) and Australia) which minimises the risk of language bias in the results.

3.1. Searching the literature

A single technique for scoping and searching the literature was not sufficient to conduct a systematic review. Hence, a multiple approach was needed with a combination of search techniques to make sure that all relevant research has been identified. These techniques included database and grey literature searching, reference list checking, citation searching, hand searching and contacting experts (Wilson, 1992, Booth et al., 2011).

The primary method for mapping the FCA literature was database searching for original research papers in English language journals. The following databases were considered appropriate for searching FCA papers: Google Scholar, Science Direct, Emerald Insight, Wiley Online and Web of Science. Database searching was supplemented by grey literature searching, reference list checking and citation searching to reduce the impact of publication bias. Finally, the identified list of studies was sent to Prof. Jan Bebbington (a highly respected and knowledgeable authority in the research field of FCA) for consultation to make sure that all relevant studies had been found.

3.2. Quality assessment of FCA studies

A methodological quality assessment of identified studies is an essential part of a comprehensive and systematic literature review (Denyer and Tranfield, 2009, Tacconelli, 2010). An initial quality evaluation was based on the type of study design being used and their hierarchy (experimental trials, observational studies, expert opinion). A detailed quality assessment of each study was based on ‘quality instruments’ in the form of checklists and quality scores (Kitchenham and Charters, 2007, Petticrew and Roberts, 2008, Denyer and Tranfield, 2009). Available lists of questions for other comprehensive reviews were assessed in the context of this study and the most relevant quality evaluation questions were selected for this review process. The checklist for the quality assessment of FCA studies considered individual aspects of the quality of FCA methods.

3.3. Study selection process

The process of selecting FCA studies based on the review protocol is presented in Figure 6. The combination of different search techniques provided 4381 records in total. Initial screening and examination of the titles and abstracts excluded 4276 records where FCA was only mentioned (book reviews, comments or papers not related to FCA) or was of secondary importance. The full text had to be assessed against the inclusion criteria when the relevance of the study was impossible to judge based only on the title and abstract. After more detailed examination another 53 papers were excluded from the review process. The remaining papers were sent to an expert (Prof Jan Bebbington) for consultation and validation which resulted in one more FCA study identified and added to the review.

Fifty-three publications were selected for the quality assessment, each study was examined in detail to assess the validity of its evidence base. The quality assessment based on study design excluded three observational qualitative studies from the review process due to their inability to answer the research question. Four other studies did not provide sufficient information about the method (system boundaries) and were also excluded from the review. Forty-six FCA studies were selected for the review process including 35 empirical (experiments and case studies) and conceptual FCA applications.

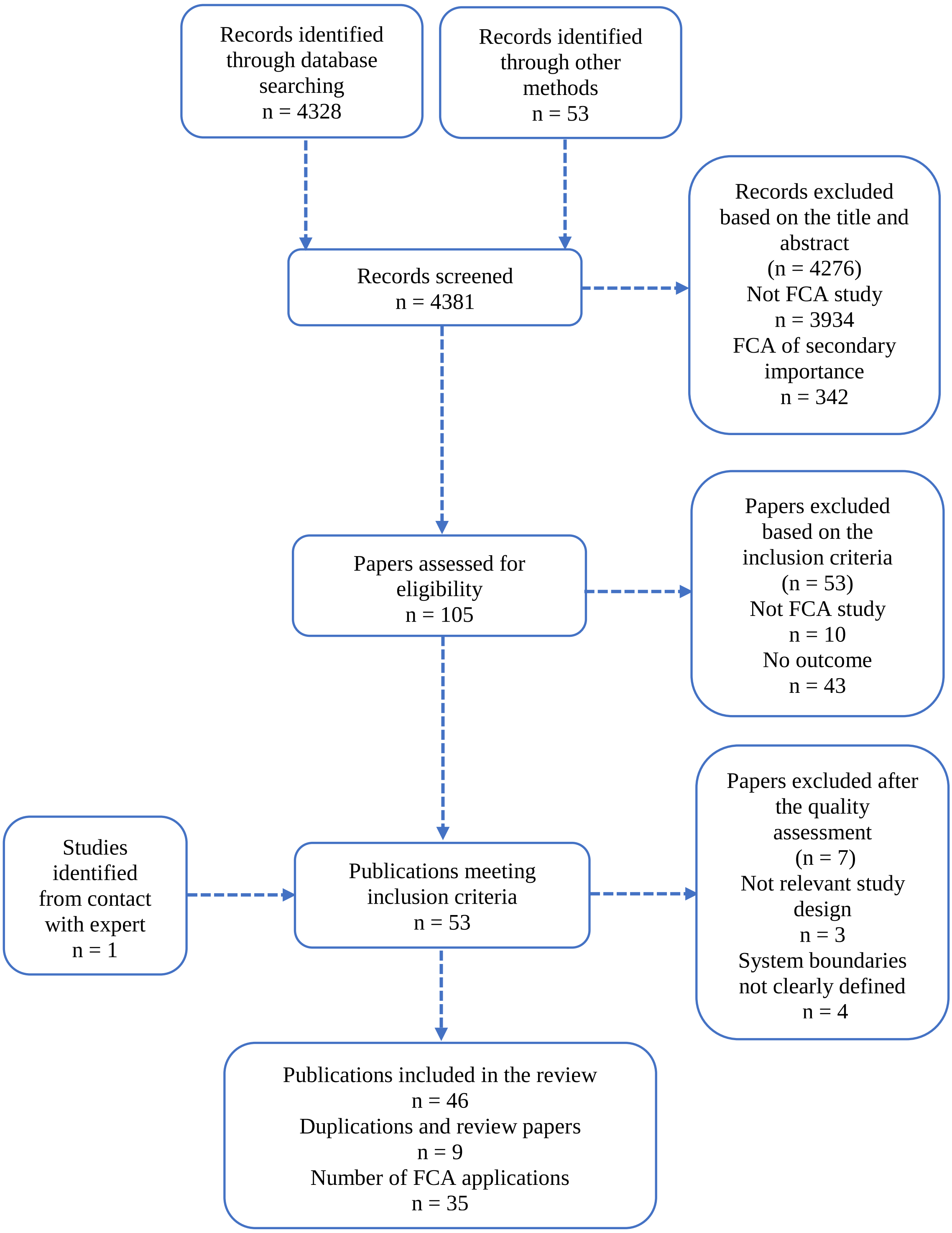

Fig. 6 The FCA study selection process used in the literature review

3.4. Data extraction and analysis

Data from 46 papers were extracted through the data extraction form. A typical data extraction form contains the following details: author and publication, paradigm, the aim and focus of the paper, the method used and theory or models (Jesson et al., 2011). A database of FCA studies was then built with the help of Microsoft Access software and based on the selected categories. Furthermore, a short summary of each study was uploaded into the database after detailed examination.

Narrative synthesis was applied to fully interpret the collected evidence. The narrative synthesis process was broken down into three steps: organising the description of studies into logical categories, analysing the findings based on each category and synthesising these findings across all studies (Petticrew and Roberts, 2008, Booth et al., 2011). Narrative synthesis recognised patterns in the evidence base and extrapolated the four major categories that have been used to assess, compare and group FCA methods:

a) **Cost focus** – an FCA study should include and allocate both internal and external impacts when assessing the performance of an object. FCA methods that consider only internal impacts neglect the major principle behind the concept of measuring and allocating environmental and social externalities.

b) **System boundaries** – although the definition of system boundaries always remains the choice of a specific company, it is also a distinctive factor between FCA methods. A simple two-point scale (narrow and wide boundaries) was assigned to each study to facilitate the analysis. In this study, narrow boundaries were interpreted as a company focusing only on its own direct impacts. Wide boundaries were interpreted as the extended system that may include both upstream and downstream impacts or take the full life cycle approach.

c) **Valuation techniques for social and environmental impacts** – different FCA methods favour different valuation techniques.

d) **Sustainability dimensions** – existing FCA methods focus on a single dimension, a combination of any two dimensions or all three dimensions of sustainability.

Clear and detailed tables were developed based on the categories to increase the transparency of the review. Finally, cross tabulation and cross-study synthesis (see Petticrew and Roberts, 2008) were applied to explore any analogies, similarities and differences between the FCA methods.

3.5. FCA methods identified in the literature

The literature review revealed ten FCA methods with a diverse level of consistency in practical applications (see Table 2). Most of these methods remain incomplete, with only a few practical applications. Some approaches are unique and stand alone, whilst other methods have been built by a number of related studies over the course of the last several decades. Table 2 compares the major methodological differences between these methods, whilst their main characteristics and descriptions are in **Submission 2**.

The comparison of the FCA methods suggested the SAM as the most complete FCA approach available in the literature and potentially attractive option for automotive organisations. The SAM is the outcome of cooperative work between British Petroleum (BP) and the University of Aberdeen. It was developed to make external costs more central to organisational decision-making (Bebbington et al., 2007). It articulates economic, resource, environmental and social issues in a project's evaluation in the form of 22 performance indicators which are then translated into monetary units primarily by using the damage cost approach. The output of the assessment is a graphical presentation (called the SAM signature, see Figure 7) of positive and negative impacts (Bebbington, 2007).

Table 2 FCA methods identified through the literature review

Methodological stream	Type of information (internal and external impacts)	Scope (direct and indirect effects)	Sustainability dimensions	Monetisation method	Related studies
1. Sustainability Assessment Model (SAM)	Internal and External	Wide	Integrated	Damage cost	(Baxter et al., 2003); (Bebbington and Frame, 2003); (Baxter et al., 2004); (Bebbington and MacGreagor, 2005); (Cavanagh, 2005); (Cavanagh et al., 2006) (Bebbington, 2007); (Bebbington et al., 2007); (Cavanagh et al., 2007); (Xing et al., 2007); (Davies, 2009); (Frame and Cavanagh, 2009); (Xing et al., 2009); (Fraser, 2012)
2. Forum for the Future (FFF)'s sustainability accounting methodology	Internal and External	Narrow	Mainly environmental	Avoidance/ Remediation cost	(Gray, 1992); (Huizing and Dekker, 1992); (Rubenstein, 1994); (Howes, 2000); (Bebbington and Gray, 2001); (Howes, 2002); (Bent and Richardson, 2003); (FFF, 2003); (Howes, 2004); (Bent, 2006); (Taplin et al., 2006)
3. US Environmental Protection Agency (USEPA)'s methodology	Internal (One external study)	Narrow and wide	Economic (one environmental study)	Market methods	(USEPA, 1997); (USEPA, 1998); (Karagiannidis et al., 2008); (Debnath and Bose, 2014)
4. Monetised LCA approach	Internal and External	Wide	Environmental, Human health	Multiple	(Steen, 1999); (Antheaume, 2004); (Epstein et al., 2011)
5. Sustainability Value (SV) Concept	Internal and External	Narrow	Integrated	Opportunity cost	(Atkinson, 2000); (Figge and Hahn, 2005); (Figge et al., 2008)
6. ExternE	External	Wide	Environmental, Social	Multiple	(Bickel et al., 1997); (Krewitt, 2002); (Bickel and Friedrich, 2005)
7. PUMA Environmental Profit and Loss Account (E P&LA)	Internal and External	Wide (excluding downstream)	Environmental	Multiple	(PUMA, 2010); (PPR, 2012);
8. Ontario Hydro	Internal and External	Wide	Environmental, Human health	Damage cost	(USEPA, 1996); (CICA, 1997);
9. Centre for Waste Reduction Technologies (CWRT)	Internal and External	Narrow	Economic, Environmental	Damage cost	(CWRT, 1999)
10. Extended LCC	Internal and External	Wide	Economic, Environmental	Damage cost	(Roth and Ambs, 2004)

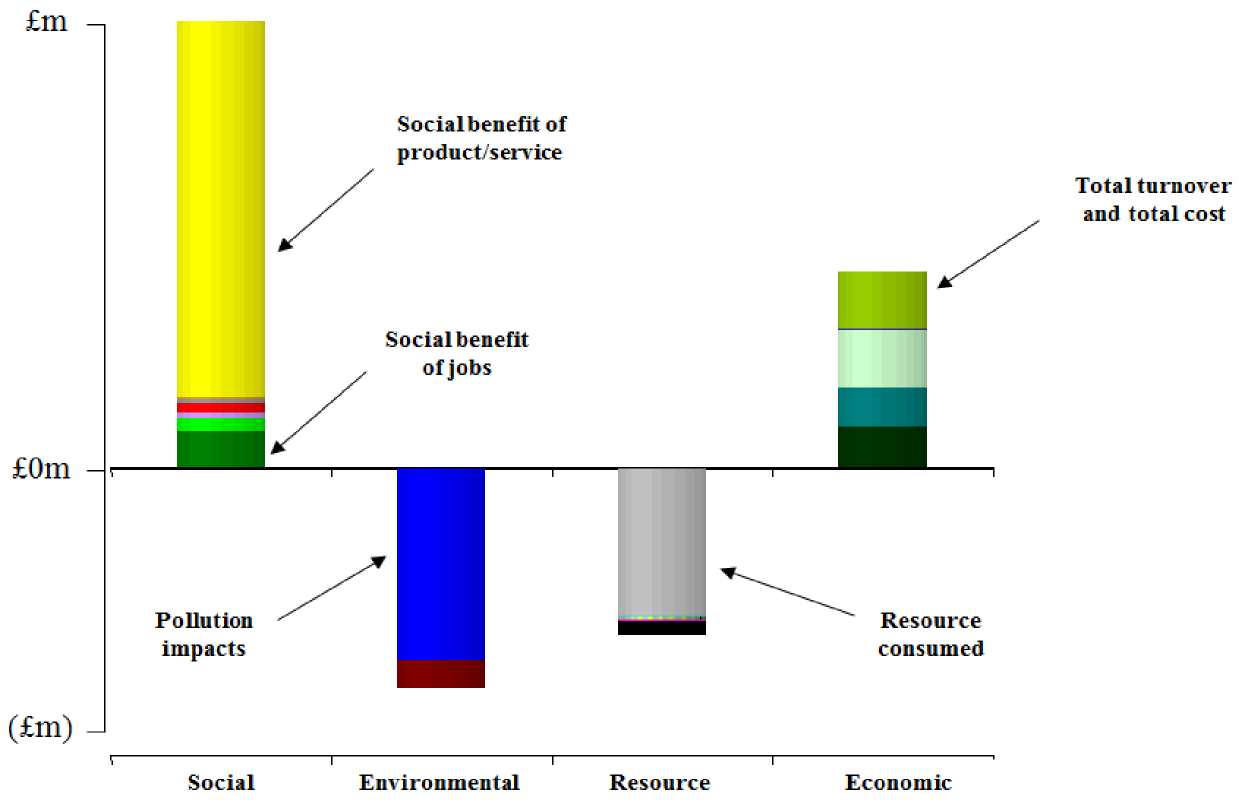

Fig. 7 The SAM signature developed for the oil and gas organisation (source: Bebbington et al., 2007).

The SAM, in contrast to other FCA methods, provides a comprehensive picture of sustainability performance by covering a wide range of economic, environmental and social assessment criteria. It takes the full life cycle approach which creates a basis for assessing the sustainability of an automobile and is in line with the widely-accepted ISO 14040 standards (Schmidt and Taylor, 2006, Mayyas et al., 2012, Arena et al., 2013).

Finally, the SAM resolves the compensation issue for which monetisation of sustainability impacts have been heavily criticised in the literature. Compensation means offsetting bad performance of one criterion with good performance of another criterion which is possible when data is monetised (Munda et al., 1995). The SAM represents the non-compensatory and strong form of sustainability when presenting data by grouping all impacts into separate criteria. Thus, data are disaggregated, which also eliminates the risk of losing some information.

The literature review suggested the SAM as the most complete FCA method that is capable of supporting the construction of a system for automotive sustainability assessment. The SAM was presented to Sustainability Engineering and Corporate Social Responsibility departments in JLR in order to obtain their feedback. Both departments showed interest in the SAM and appreciated its holistic approach and potential to enhance business decision-making for sustainability. Its measurement of a broad range of economic, environmental, resource and social effects (both internal and external), ability to provide monetary metrics together with physical metrics for sustainability assessment, and ability to combine multiple sustainability dimensions were of particular importance to JLR. Furthermore, both departments appreciated that the SAM is an ideologically open and flexible concept, which can be subsequently applied in different configurations and decision levels, including the policy, project, product, process, material or strategy level.

Hence, it was agreed for this EngD to focus on the development of automotive SAM (named A-SAM), by adapting the process and research methods described in the next sections of this Innovation Report.

4. Adapting the FCA method to the automotive setting

The process of developing the A-SAM was adapted from the literature and is presented in Figure 8. This process is versatile for all types of FCA exercises.

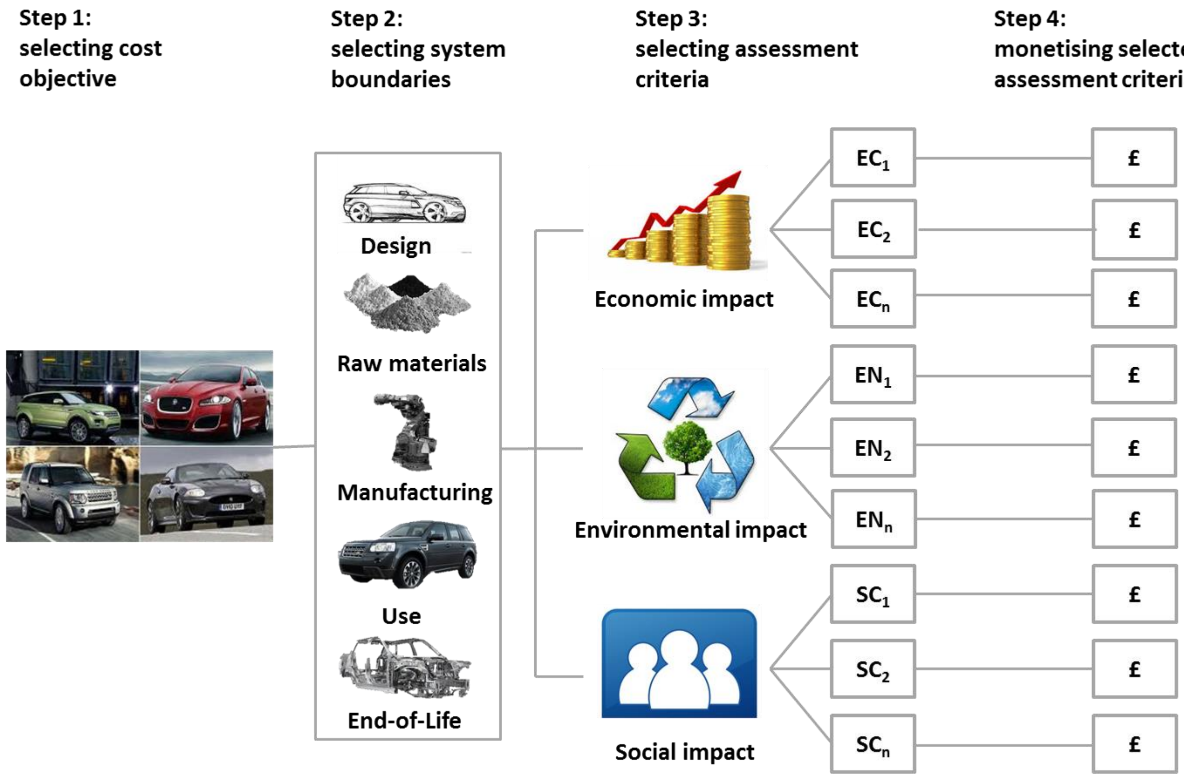

Fig. 8 The process of adapting the SAM to the automotive setting (adapted from: Bebbington et al., 2001 and Bebbington, 2007)

Steps 1 and 2 were straightforward and they were defined by considering the need of JLR and the characteristic of the automotive sector defined in Sections 1 and 2 of this Innovation Report. Hence, the primary cost objective of the A-SAM was to support product development decisions by assessing which of two or more concepts (e.g. products, processes, or materials) are the most optimal from the sustainability perspective. The system boundaries were defined wide by considering all potential impacts throughout the product life cycle. **Steps 3 and 4** were much more sophisticated and required clear-cut methodological requirements.

This section demonstrates the research approach used for **steps 3** in the process of developing the A-SAM.

4.1. Developing a framework for the A-SAM

Every industry varies and generates different types of social, environmental and economic effects; therefore, adapting the SAM to the automotive setting required the development of a new set of assessment criteria for **step 3**. Sustainability assessment criteria and indicators almost always play a fundamental role in any evaluation of sustainability (Ramos, 2009, Singh et al., 2009, Cinelli et al., 2014).

Automotive sustainability assessment criteria can be found in the literature; however, there has been no clear consensus amongst automotive experts and other stakeholders on which criteria are critical and which framework should be used as a standard. The major limitations of existing frameworks stem from the area they cover. For example, Olugu et al. (2011) developed a key environmental performance measures for the automobile supply chain only. Other methods, such as Volvo's Environmental Priority Strategies (EPS) system (Steen, 1999), as well as automotive life cycle assessment (LCA) frameworks (Arena et al., 2013; Del Duce et al., 2013; Rivera and Reyes-Carrillo, 2015), extend the scope of the assessment to the entire life cycle of the vehicle, but they are still limited to environmental assessment only and ignore the social and economic spheres. Ford, with its Product Sustainability Index (PSI), made a first attempt to reflect the triple bottom line vision of sustainability; however, this model still suffers from a lack of complete coverage of sustainability metrics. Ford included only five environmental, two social and one economic criteria in its PSI (see Schmidt and Taylor, 2006).

Taking into consideration all of these limitations, it was evident that a holistic framework covering a comprehensive set of sustainability criteria for automotive sustainability assessment was still missing and had to be defined in this EngD project.

The development of a framework for the A-SAM involved two major steps. Initially, a set of sustainability assessment criteria was selected from the literature to create a conceptual draft of the framework. These criteria were then critically evaluated by a multidisciplinary panel of automotive experts. The selection of a diverse group of experts was critical to ensure the credibility, transparency and robustness of the process (Buchholz et al., 2009, Carrera and Mack, 2010, Ramos and Caeiro, 2010). Figure 9 summarises the research approach.

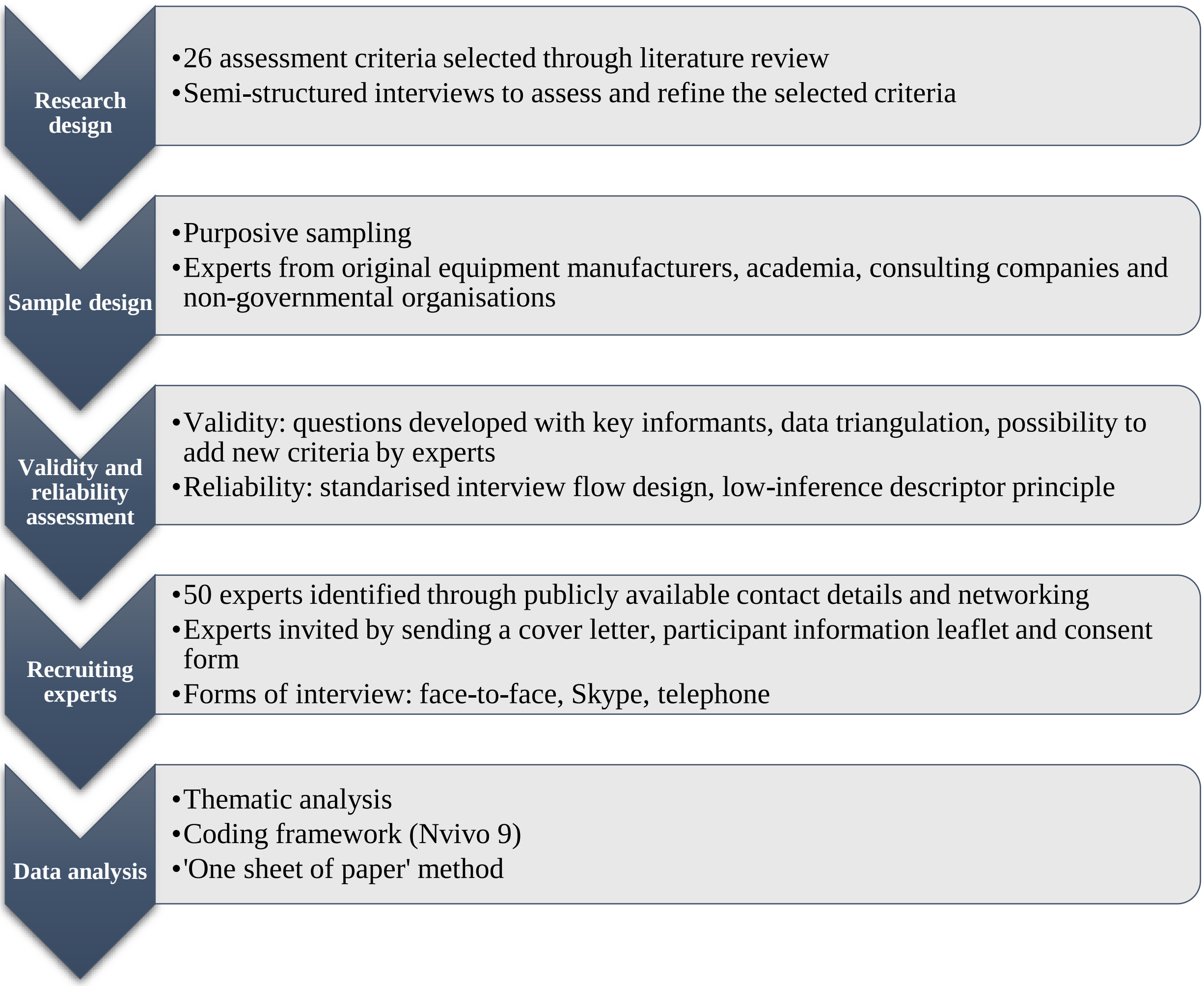

Fig. 9 A summary of the research methods used for the interview study

4.1.1. Automotive sustainability assessment criteria selected from the literature

In order to identify and select assessment criteria for the framework, relevant literature on automotive sustainability assessment was reviewed, including existing frameworks and models, company reports, original theoretical and practical research papers and recommendations from relevant institutions (e.g. The European Commission (EC)). The following set of published guidelines was adopted to aid the criteria selection and refinement process (Akadiri and Olomolaiye, 2012 and Akadiri et al., 2013):

- **Comprehensiveness:** the chosen criteria should demonstrate progress towards all dimensions of sustainability.
- **Applicability:** the chosen criteria should be applicable across a range of alternative options in order to ensure comparability.
- **Transparency:** the criteria selection process should be transparent to all stakeholders.
- **Practicality:** the chosen criteria should be practical in the sense of the tools, time and resources available for analysis and assessment.

The criteria selected for the automotive sustainability assessment framework and an explanation of each criterion are presented in Table 3. Elkington's (1999) triple bottom line model distinguishes three major categories of sustainability: economic, environmental and social. The automotive industry is one of the most resource-intensive industrial systems in the world (Mildenberger and Khare, 2000); therefore, for practical reasons and similarly to the original SAM, assessment criteria have been grouped into four major categories:

- **Economic impact:** the original SAM takes a value-based approach and measures the economic benefits from a project from different stakeholder perspectives (share in total revenue). However, the LCC method is usually applied to measure the economic dimension of products (see Griesshammer et al., 2007) as well as automobiles (Schmidt and Taylor, 2006, Goedecke et al., 2007).

Table 3 Assessment criteria selected for the framework based on the literature review

Category	Assessment criteria		References
Economic impact	Money to contractors	All expenditures paid to contractors/suppliers (material and service costs)	(Cuenca et al., 1999); (MacLean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
	Production cost	Manufacturing cost, warranty charges, research and development, depreciation/amortisation of tooling and facilities	(Cuenca et al., 1999); (MacLean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
	Acquisition cost	Distribution, advertising and dealer support cost, gross margin per car	(Cuenca et al., 1999); (MacLean and Lave, 2003); (Goedecke et al., 2007); (Ciroth et al., 2008)
	Operating and maintenance cost	Fuel, insurance, taxes, cost of washing, financial service, parts and servicing cost	(Cuenca et al., 1999); (MacLean and Lave, 2003); (Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Ciroth et al., 2008); (Mayyas et al., 2013)
	End-of-life cost	Disposal cost/residual value	(Schmidt and Taylor, 2006); (Goedecke et al., 2007); (Mayyas et al., 2013)
Environmental impact	Global warming potential	Greenhouse gas emissions contributing to global warming	(Graedel and Allenby, 1998); (Schmidt and Taylor, 2006); (Manfredi et al., 2012); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Stratospheric ozone depletion	Thinning of the stratospheric ozone layer due to anthropogenic emissions such as chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs)	(Graedel and Allenby, 1998); (Del Duce et al., 2013)
	Photochemical ozone creation potential	Volatile organic compounds (VOCs) and nitrogen oxides which react in the presence of sun and cause ground-level ozone concentration	(Graedel and Allenby, 1998); (Schmidt and Taylor, 2006); (Manfredi et al., 2012); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Acidification potential (terrestrial and aquatic)	Increase in the number of acid rain-producing substances such as sulphur dioxide, nitrogen oxides, ammonia, hydrogen chloride, hydrogen fluoride and hydrogen sulphide	(Graedel and Allenby, 1998); (Manfredi et al., 2012); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Eutrophication potential (terrestrial and aquatic)	All potential impacts of excessively high levels of macronutrients such as nitrogen compounds (fertilisers), phosphorous compounds and organic matter	(Graedel and Allenby, 1998); (Manfredi et al., 2012); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Eco- and human toxicity	Emission of toxic substances to the air, water and soil over accepted limits	(Graedel and Allenby, 1998); (Manfredi et al., 2012); (Del Duce et al., 2013); (Hawkins et al., 2013)
	Particulate matter formation	Hazardous solid and liquid particles (organic and inorganic) in the air such as pollen, dust, smoke and liquid droplets	(Manfredi et al., 2012); (Hawkins et al., 2013)
Resource impact	Energy consumption	Resource depletion due to energy consumption	(Graedel and Allenby, 1998); (Steen, 1999); (Nunes and Bennett, 2010); (Manfredi et al., 2012); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013)

	Water consumption	Water depletion due to fresh water and industrial water consumption	(Graedel and Allenby, 1998); (Nunes and Bennett, 2010); (Manfredi et al., 2012); (Arena et al., 2013)
	Renewable and recyclable materials	Renewable and recyclable materials used	(Graedel and Allenby, 1998); (Steen, 1999); (Schmidt and Taylor, 2006); (Nunes and Bennett, 2010); (Manfredi et al., 2012); (Arena et al., 2013); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Other non-renewable and non-recyclable materials	Resource and minerals depletion due to non-renewable and non-recyclable materials consumption	(Graedel and Allenby, 1998); (Steen, 1999); (Nunes and Bennett, 2010); (Manfredi et al., 2012); (Del Duce et al., 2013); (Hawkins et al., 2013); (JLR, 2013)
	Land use	Loss of land as a resource in the sense of it being temporarily unavailable	(Nunes and Bennett, 2010); (Arena et al., 2013) (Del Duce et al., 2013)
	Resource consumed during customer use	Depletion of resources and minerals due to fuel, oil, filters, lubrication, tyres, batteries used	(Graedel and Allenby, 1998); (Arena et al., 2013)
Social impact	Vehicle users and pedestrian safety	The level of safety of vehicles (i.e. Euro NCAP rating)	(Schmidt and Taylor, 2006); (Arena et al., 2013)
	Drive-by noise	The social impact of sound and the sound pressure level from engines, exhausts and rolling noise	(Schmidt and Taylor, 2006); (Goines and Hagler, 2007); (Arena et al., 2013); (Del Duce et al., 2013)
	Vibration	The whole-body vibration impact on the driver's health, such as musculoskeletal and lumbar spine disorders	(Wikström et al., 1994); (Wilder and Pope, 1996); (Makhsous et al., 2005); (Griffin, 2007); (Mayyas et al., 2013)
	Vehicle interior air quality	VOCs emitted from the materials and finishes used to make vehicle interior	(Brown and Cheng, 2000); (Schmidt and Taylor, 2006); (Geiss et al., 2009); (Arena et al., 2013)
	Human health effects from external air quality	Human health effects as a result of particulates, ozone, polycyclic aromatic hydrocarbons, heavy metals emission	(Steen, 1999); (Kampa and Castanas, 2008);
	Mobility capability	Number of seats and luggage capacity, ability to accommodate elderly, handicapped and disabled passengers	(Schmidt and Taylor, 2006); (Nunes and Bennett, 2010)
	Employment	Product-based employment	(Schmidt, 2007); (Nunes and Bennett, 2010)
	Occupational health and safety	Occupational health and safety performance (injury and illness rate)	(Benoît et al. 2010); (see Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)
	Labour rights	Freedom of association, child labour, forced labour, discrimination, remuneration, working hours	(Benoît et al. 2010); (see Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)
	Human rights	Women's rights, indigenous people's rights, resettlements, conflict minerals, corruption, cultural and sacred heritage, access to resources, development of local communities	(Benoît et al. 2010); (Epstein and Yuthas, 2011); (see Traverso et al., 2013); (Aluminium Stewardship Initiative, 2014)

- **Environmental impact:** covers the environmental impact (pollution) and the environmental damage caused by automobiles.
- **Resource impact:** covers the external impacts of resources consumed by an automobile that are not fully accounted for in the economic impact section. This includes all renewable and non-renewable resources that once used cannot naturally be replaced and employed for alternative uses in the future.
- **Social impact:** covers the social impacts (negative and positive) of an automobile.

These criteria were then the subject of consultation with a multidisciplinary panel of automotive experts in step two.

4.1.2. Research instrument design

Different research methods and instruments were used in the literature to obtain expert input into the process of developing the sustainability assessment criteria. These included an expert workshop (Whitmarsh et al., 2009, Xing et al., 2009), a survey (Buchholz et al., 2009, Olugu et al., 2011, Akadiri and Olomolaiye, 2012), interviews (Wallbaum et al., 2012, Arena et al., 2013) or a combination of all three (Carrera and Mack, 2010, Rall and Haase, 2011). Bringing together international experts from different disciplines and organisations into a group workshop was beyond the practicalities of this EngD. Survey research was also considered inadequate for this study due to the following potential issues (Gillham, 2000, Gray, 2004, Silverman, 2011):

- Survey-based approaches require access to a very large population of experts from the automotive sector in order to get a meaningful return.
- Survey research can cause a range of potential biases as responses are usually anonymised and it is impossible to verify whether a respondent is an expert in a given area or not.

- Obtaining depth and insight were considered more important for this research than breadth and representativeness of data. Sustainability assessment may take different approaches and interpretations; it is therefore important to clarify misunderstandings and interpretation.

Interviews with high-level experts within the automotive industry (both practitioners and academics) was selected as the most appropriate method to support development of a framework for automotive sustainability assessment. Qualitative interviewing provides a level of depth and complexity not available to other research instruments (Silverman, 2011). Open-ended and flexible questions are more likely to receive a considered response than closed questions and therefore provide better access to individuals' perceptions, views, values, opinions, understandings and experiences (Gillham, 2000, Gray, 2004, Silverman, 2011).

4.1.3. Sample design

A qualitative research does not aim to draw statistical inference or produce a statistically representative sample and therefore non-probability samples are well suited to the small-scale, in-depth interview study (Ritchie et al., 2003, Wilmot, 2005). One technique often used in non-probability sampling is purposive sampling (also called judgement sampling), which assumes the deliberate selection of key informants based on qualities possessed by the informants (Wilmot, 2005, Tongco, 2007). In purposive sampling, the goal is not to generalise to a population but to obtain insight into events, individuals or phenomena (Onwuegbuzie and Leech, 2007). A researcher decides what needs to be known and selects appropriate and reliable informants who are willing to provide the required information according to their knowledge and experience (Tongco, 2007).

The question of how an expert is defined is largely unresolved and clear quality criteria for selecting experts were not found in the literature; therefore, it was necessary to decide which criteria to use for the process of selecting experts. This selection process can be based on attitudes, demographic characteristics, experience, list of qualifications or any kind of phenomena (Ritchie et al., 2003, Tongco, 2007). For example, Olugu et al. (2011) defined academic experts in the area of green automotive supply chain management based on their contribution and publications in the field of supply chain management, while experts from the automotive industry were selected based on their position and number of years' experience in the automotive supply chain. Experts for this study were selected using the following criteria:

- decision influencers in original equipment manufacturers (OEMs) (e.g. directors, heads of department, senior managers, leaders, technical specialists) with a minimum of three years' professional experience in the area of sustainable automotive systems;
- academics who publish extensively on the topic of green and sustainable automotive systems;
- consultants and advisory bodies with a proven track record of working with automotive organisations in the area of sustainability; and,
- leaders of influential governmental and non-governmental organisations (NGOs) with expertise in the area of sustainable mobility.

Although in purposive sampling the criteria used to select key informants are more important than the number of informants (Wilmot, 2005), the choice of sample size still matters as it determines the extent to which the researcher can achieve data saturation and generalise results of the research (Onwuegbuzie and Leech, 2007). According to Guest et al. (2006) and Gray (2004), a sample of between six and twelve interviews is often sufficient to achieve data saturation for every theme. As there is no consensus as to the number of interviews required to achieve the desired research objective, the sample size representing different perspectives continually increases until such time as no new viewpoints emerge from the data (Ritchie et al., 2003, Gray, 2004). Based on these principles, the interview data in this research were studied and analysed as they were collected until it became clear that perspectives were being repeated and data saturation was reached.

4.1.4. Reliability and validity assessment

Research instruments, whether used as part of a quantitative or qualitative study, should be designed to provide credible findings (Silverman, 2011, Gray, 2004, Tongco, 2007). Two central concepts should be considered when discussing the credibility of scientific research – validity and reliability (Silverman, 2011). A research instrument is valid when it measures what it was intended to measure, and is reliable when it consistently measures what it was set out to measure (Gray, 2004).

Although these concepts are more rigidly applied in quantitative research, there are instruments and indicators that to a certain extent ensure the credibility of qualitative study (see Gray, 2004, Tongco, 2007, Silverman, 2011). Validity of this interview study was strengthened by:

- developing interview questions with the assistance of key informants;
- interviewing reliable and knowledgeable informants;
- data triangulation by comparing a developed set of assessment criteria with the literature; and,
- providing experts with the opportunity to add and discuss new assessment criteria.

Reliability and consistency of the research instrument and results were strengthened by following the standardised interview flow design and adapting the low-inference descriptors principle (Gillham, 2000, Gray, 2004, Silverman, 2011). The intention of the low-inference descriptors principle is to eliminate the risk of influencing the reporting by the researcher reconstructing the general sense of what respondents said (Silverman, 2011). This risk was eliminated by tape-recording all interviews to obtain as concrete and accurate responses as possible.

4.1.5. Recruiting experts for the study

Fifty experts in the field of sustainable mobility were identified as potential research participants. Their contact details were either publicly available or were gained through networking activities. Experts were invited to participate in this study through the sending of a cover letter, participant information leaflet and consent form.

Potential interviewees were selected mainly from the developed countries, such as the UK, Germany, Italy, Sweden, France, Switzerland and the USA. This is due to the fact that the world's largest car manufacturers are located in developed countries and therefore experts from these countries were easier to identify and access. In order to minimise costs and travelling, telephone and video interviews were used in addition to face-to-face interviewing. Twenty-four interviews were conducted between April and July 2015. The duration of interviews ranged from 19 to 42 minutes, excluding introduction but including discussion of other topics.

4.1.6. Analysing data – thematic analysis

Thematic analysis, next to content analysis, is the principal technique used by researchers to analyse qualitative data and is a process of encoding qualitative information (Boyatzis, 1998, Marshall and Rossman, 1999, Braun and Clarke, 2006). There are a number of similarities between content analysis and thematic analysis (such as searching for patterns and themes and cutting across data), but the main difference lies in the opportunity for quantification of data in content analysis by measuring the frequency of different themes and categories (Vaismoradi et al., 2013). Quantification of the data obtained in this study was not critical as gaining a deep level of understanding of a wide range of perspectives and experiences was far more important than replicating their frequency among the wider population. Hence, thematic analysis was selected to analyse the data obtained from interviews.

All interview questions and answers went through a process of word-for-word transcription. Once all interviews had been transcribed, they were read several times to obtain a broader understanding of the data and to generate initial ideas regarding all of the themes and categories. Boyatzis (1998) and Braun and Clarke (2013) outlined three major methods of developing themes, categories and codes based on existing theory, the data collected and prior research. A combination of the first two methods was used to develop the coding framework and all interview data were coded against 6 themes and 30 categories with the assistance of NVivo 9 (the coding framework is provided in appendix 6 in **submission 3**).

A 'one sheet of paper' (OSOP) analysis, a method developed by the University of Oxford for interpreting qualitative data, was performed in order to better understand the data and to potentially reduce the number of themes and categories. The OSOP analysis involves reading through each section of the data and noting on a single sheet of paper all issues raised by the different coded extracts, along with the relevant respondents' IDs. Once the OSOP is completed, a summary of all the issues within the code (category) and the IDs of relevant respondents next to them is created (see Ziebland and McPherson, 2006 for more details about the OSOP).

4.2. Refining the framework based on expert input

Of the 50 experts invited to participate in this study, 24 were interviewed, representing different sectors, organisations, roles within their respective organisations and their number of years' professional experience. (see Table 4 for details).

Table 4 Anonymised list of experts that participated in this study

Participant identifier	Interview date	Sector	Role in organisation	Years of experience
A1	15/04/2015	Academia	Director of Automotive Research Centre	20+
A2	15/04/2015	Academia	Co-Director of Automotive Research Centre	20+
A3	24/04/2015	Academia	Lecturer - Consultant	5
A4	06/05/2015	Academia	Associate Professor	20
A5	07/05/2015	Academia	Programme Manager	5
A6	15/05/2015	Academia	Research Fellow	18
A7	18/06/2015	Academia	Professor - Vehicle Powertrain	20+
A8	25/06/2015	Academia	Adjunct Professor – Environmental System Analysis	20+
C1	18/05/2015	Consultancy	Vice President Mobility	20+
C2	29/06/2015	Consultancy	Managing Consultant	16
C3	10/07/2015	Consultancy	Principal Consultant	15
C4	15/07/2015	Consultancy	Director	20+
N1	08/06/2015	NGOs	Principal Adviser – Sustainable Mobility	20
N2	10/07/2015	NGOs	Managing Director	20+
N3	17/07/2015	NGOs	Head of Sustainable Business	3
N4	20/07/2015	NGOs	Programme Manager	20+
O1	05/05/2015	OEMs	Sustainability Engineer	14
O2	05/05/2015	OEMs	Sustainability Engineer	11
O3	05/05/2015	OEMs	Sustainability Engineer	3
O4	22/05/2015	OEMs	Director Sustainability	20+
O5	26/05/2015	OEMs	Safety Attribute Senior Manager	20+
O6	02/07/2015	OEMs	Group Environmental Strategist	15
O7	04/07/2015	OEMs	Head of Corporate Responsibility	10
O8	22/07/2015	OEMs	Principal Engineer NVH	14

This section only summarises changes in the A-SAM framework based on expert input. More detailed results of the interview analysis, including general comments about the framework and an analysis of each individual section of the framework, are available in **Submission 3**.

The environmental section of the framework did not change much as the interviewees raised no significant concerns regarding the environmental criteria. These metrics are well defined and recommended by relevant institutions, for example, the EC (EC-JRC, 2011, Manfredi et al., 2012). The resource consumed during customer use metric was excluded from the framework due to the potential for double counting. Renewable, recycled and reused materials were incorporated into the resource and minerals consumption impact category in the sense that they will either reduce or increase this impact depending on whether they are primary or secondary materials. This assessment should be performed at the life cycle inventory level (Vieira et al., 2016).

The economic assessment in the framework is primarily focused on LCC analysis, which is a common approach for products recommended by both the literature (see Schmidt and Taylor, 2006, Grießhammer et al., 2007) and interviewees. The A-SAM framework recognises the macroeconomic impact of cars, including their contribution to gross profit, dividends, taxes and gross value added, but all of the interviewees suggested that this level of aggregation is more relevant at the corporate than at the product level.

The social impact assessment is relatively new for businesses due to the lack of a set of widely accepted standards for measuring the social performance of products. Hence, expert input was critical for developing the social section of the framework. Congestion was identified as an important social and also economic impact of cars that was missing from the framework. Congestion was not included in the original set of criteria because the literature recognises congestion as an impact of the whole transportation system (see Maibach et al., 2008, Korzhenevych et al., 2014), thus making it difficult to apportion to a specific vehicle. However, the interviewees pointed to technological developments facilitating a comparison between two different vehicles and their potential impacts on road traffic.

Although the interviewees made no clear suggestion to include vibration in the sustainability assessment, Mayyas et al. (2013) cited noise and vibration performance as important societal factors in the design process of sustainable automotive bodies.

The interviewees also made recommendations regarding a number of minor issues to improve the social section of the framework. For instance, employment is not limited to the number (quantity) of jobs provided but also includes the quality aspect of these jobs (e.g. occupational health and safety, labour rights, wages, etc.).

Based on these comments, the A-SAM framework was constructed to represent the life cycle sustainability performance of a vehicle (see Figure 10).

The framework consists of 26 midpoint and 9 end-point impact categories. Grouping criteria into midpoints and end-points was essential to eliminate any potential overlap between criteria and the risk of double counting. For example, human health effects from external air quality in the A-SAM framework is the end-point effect of air pollutants such as PM, NO_x or VOCs. A set of end-point assessment criteria were obtained either from the interviewees or from a number of relevant studies (Steen, 1999, EC-JRC, 2011, Hauschild et al., 2013). Links between the criteria are highlighted with arrows to indicate interdependence between the sustainability dimensions. For example, the air quality impact has a social impact in terms of human health which may then result in an economic impact in the form of increased government expenditure on health.

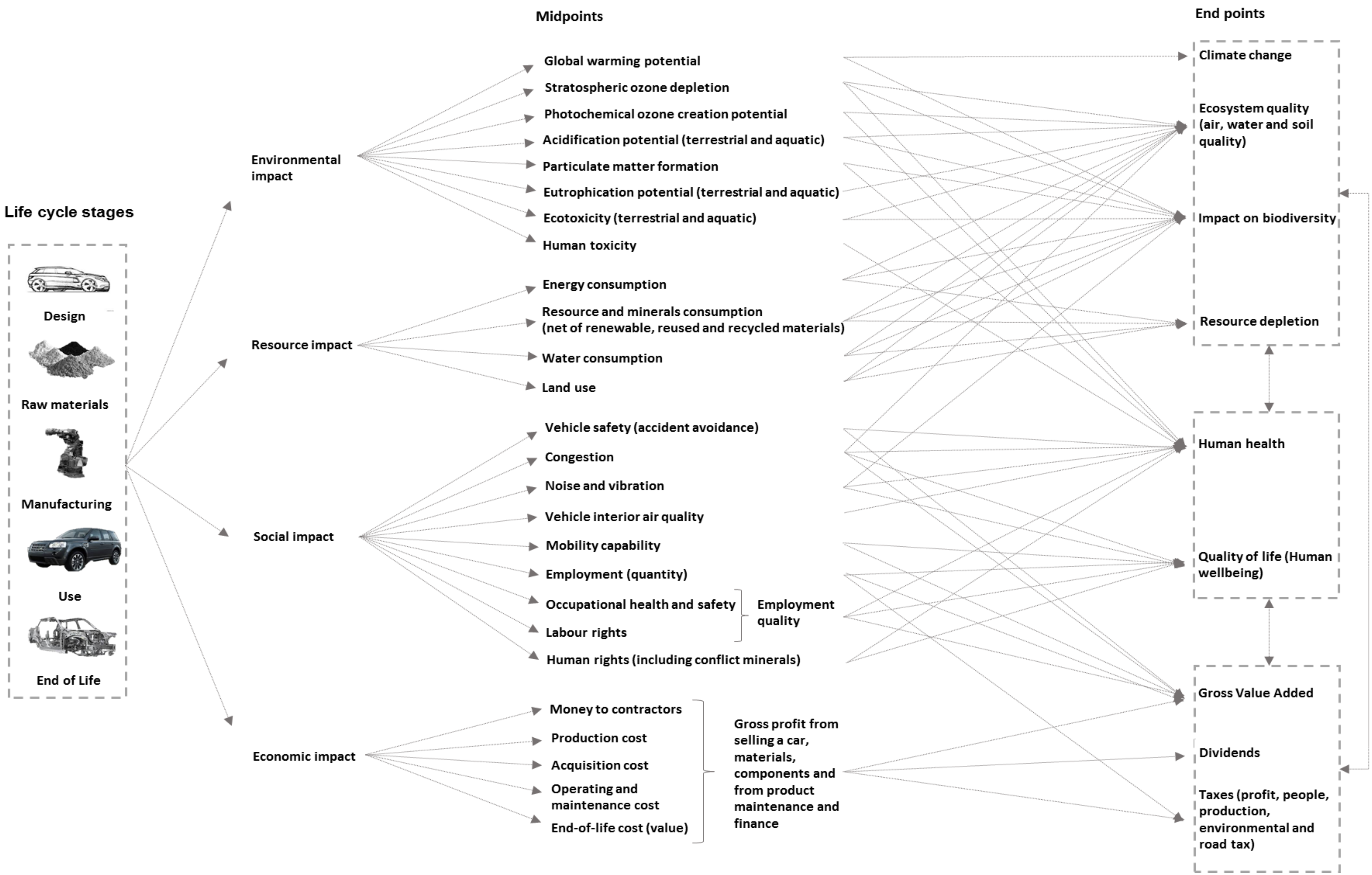

Fig. 10 The automotive sustainability assessment framework developed based on the literature and interview study

A few of the interviewees questioned the practicality of measuring upstream impacts due to the lack of reliable measurement tools and because they are outside the control of OEMs. Indeed, there are many obstacles to measuring the upstream impacts of the automotive sector, the most important being the size and complexity of the supply chain. However, existing automotive sustainability assessment tools (see Steen, 1999; Schmidt and Taylor, 2006; Arena et al., 2013) all emphasise the importance of life cycle thinking in measuring the sustainability of cars. BMW also recognised that responsible corporate governance requires examination of the environmental and social impacts generated throughout the entire life cycle of the product (see Traverso et al., 2013). The company admits that the lack of primary data for all tiers of supply is an obstacle, especially in terms of social assessment; however, from a risk management perspective, it is important to at least identify the social hot spots along the entire supply chain.

A particular contribution of the A-SAM is that it is intended to translate a range of conflicting information into a single monetary unit score. This in turn facilitates the decision-making process by identifying win-win scenarios and trade-offs between alternative options and makes these trade-offs transparent. Hence, **Step 4** in the process of developing the A-SAM invlolved converting environmental and social impacts included in the A-SAM framework into cost estimates (see Figure 8). This step is usually the most complex, time-consuming and expensive in the FCA process and it is discussed in the next sections of this Innovation Report.

5. Valuing environmental and social impacts – refining project objectives

There are a number of accounting techniques to help in the translation of social and environmental impacts into monetary values, including damage cost, cost of control, contingent valuation, hedonic pricing and travel cost methods (see Jasinski et al. 2015). However, the damage cost method is the most scientific and widely accepted technique for valuing externalities (Bickel and Friedrich, 2005, Maibach et al., 2008, Korzhenevych et al., 2014), and the primary valuation method in the original SAM (Bebbington, 2007). The damage cost method requires the full midpoint to end-point modelling (also known as Impact Pathway Analysis (IPA)), which comprises four principal steps (Bickel and Friedrich, 2005):

- **Estimating emissions:** for example, 1 kg of nitrogen oxides (NOx) emitted at a specific site.
- **Dispersion modelling:** calculating increased pollutant concentrations in all affected regions.
- **Estimating impacts:** calculating physical damage from an increased concentration using an exposure-response function (e.g. cases of asthma due to NOx and ozone concentration).
- **Valuing impacts:** converting impacts into monetary values by applying appropriate valuation techniques (e.g. revealed and stated preferences methods).

Hence, quantified emissions and other impacts (e.g. noise, vibration, congestion, vehicle safety, or human and labour rights violations) can be monetised on the basis of their end point impacts on climate change, soil, air and water quality, resource depletion, human health and wellbeing and biodiversity. This type of modelling is complex as it requires input from a wide range of professionals, such as epidemiologists, ecologists, economists, dispersion modellers, statisticians and environmental engineers (Friedrich and Bickel, 2001).

Further complexity is added based on the fact that environmental and social impacts very rarely have a price attributed to them either by the market or regulators. If this is the case, then behavioural methods (such as contingent valuation, hedonic pricing and travel costs) needs to be applied to measure the money value of a specific impact directly from the preferences or behaviour of the affected stakeholder (Bent and Richardson, 2003). Information can be obtained directly from surrogate market data or indirectly from an individual using questionnaires, surveys or experimental techniques (Milne, 1991). As with every questionnaire study, this process is time and resource intensive.

One alternative to the IPA is benefit transfer, which uses existing estimates developed for specific sites under certain resource and policy conditions and applies them to new contexts and sites with similar resources and conditions (Bickel and Friedrich, 2005). Benefit transfer is recommended when the relevant economic values and required resources are not available for the development of new estimates for site-specific impacts (Watkiss et al., 2005; Maibach et al., 2008; Korzhenevych et al., 2014).

Benefit transfer for the environmental and social impacts included in the A-SAM required a reliable and credible source of external cost estimates. A review of FCA studies revealed that apart from air quality and global warming impacts (see Watkiss et al., 2005, Maibach et al., 2008, Korzhenevych et al., 2014), there is a limited availability of damage cost estimates in the literature. This means that new valuation models had to be developed for most of the environmental and social criteria included in the A-SAM by conducting the full IPA. This, however, was not possible for this EngD considering the time and resources available and the complexity of this type of analysis.

5.1. Total Impact Measurement and Management (TIMM) model

One major FCA method not identified by the time the literature review and A-SAM framework had been completed was the TIMM model developed by PricewaterhouseCoopers (PwC). PwC is a multinational professional services company specialising in accounting audit and assurance, tax and consulting services. The TIMM model comprises 20 impact categories grouped into four major impacts: social, environmental, tax and economic (see Figure 11). Similarly to the SAM, all impact categories are quantified and monetised using the damage cost method (see PwC, 2013 for more information about TIMM).

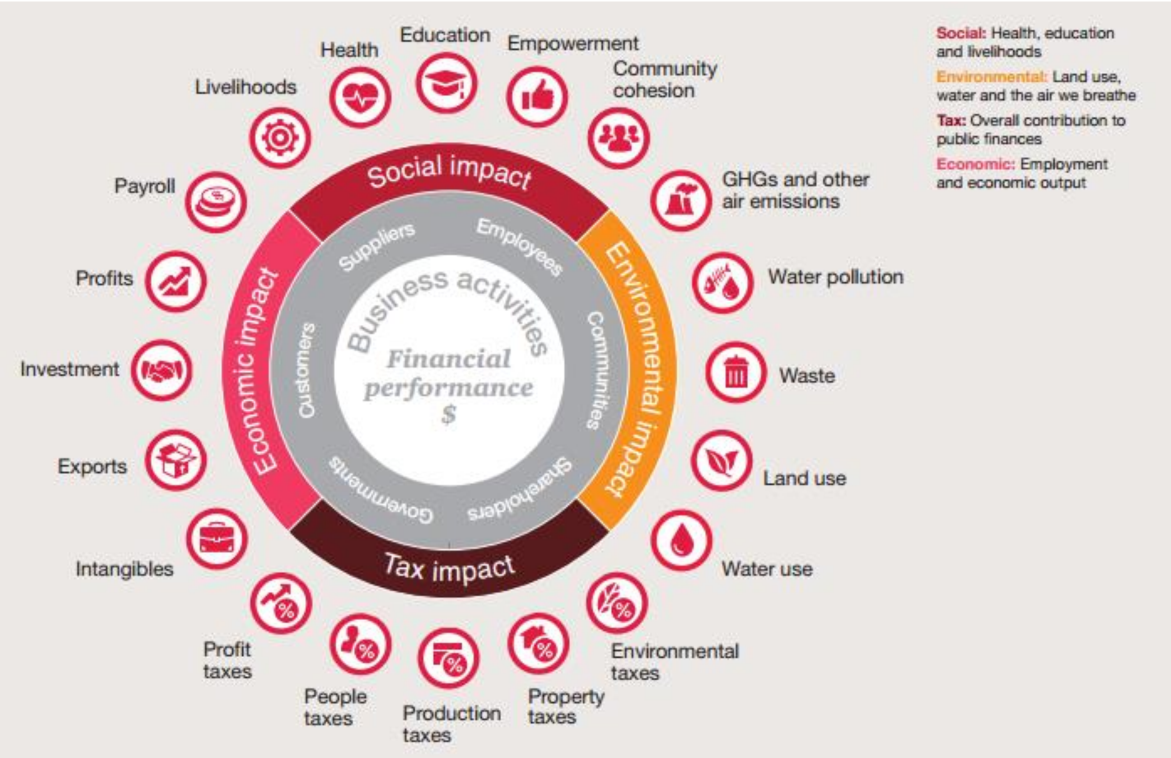

Fig. 11 The TIMM framework (source: PwC, 2013)

The TIMM model was a significant step forward in the FCA field of research that demonstrates its practical use and potential in supporting business decision-making. Other FCA studies were all theoretical with only a few examples of practical applications in the business environment (e.g. Ontario Hydro, BP and PUMA). The discovery of TIMM was a turning point in the evolution of this EngD project. JLR wanted to drive improvements in sustainability within its operations through an understanding of its total sustainability impact; therefore, the company opted to contract PwC to develop a complete set of valuation indicators for the A-SAM before the completion of this EngD project.

A meeting between JLR, PwC and the author on 3rd July 2015 introduced the A-SAM to PwC and identified overlaps and differences between the SAM and TIMM, after which JLR contracted PwC to carry out valuations for those criteria already included in the TIMM model. This provided an opportunity for this project to complement the PwC work with an automotive-specific analysis examining engineering-related areas relevant for JLR, but for which PwC was not capable to deliver a value. The comparison of the A-SAM and TIMM is presented in Table 5, and it indicated the following twelve areas in the A-SAM for which PwC could not deliver value due to the lack of expertise and gaps in the scientific knowledge:

- Stratospheric ozone depletion
- Human toxicity
- Ecotoxicity
- Resource depletion due to energy consumption
- Resources and minerals consumption
- Vehicle safety
- Congestion
- Noise and vibration
- Vehicle interior air quality
- Supply chain health and safety
- Labour rights
- Human rights

Table 5 The comparison of the A-SAM and TIMM frameworks (underlined text indicates criteria from the A-SAM which are not measured by the TIMM model)

	A-SAM	**TIMM**
Goal	To assess sustainability performance of JLR products	To assess JLR's corporate sustainability performance
Scope	Life cycle performance	JLR's impacts only
Environmental criteria	Global warming potential	Greenhouse gases
	Stratospheric ozone depletion	Other air emissions Stratospheric ozone depletion – Not measured
	Photochemical ozone creation potetntial	
	Particulate matter formation	
	Acidification potential	
	Eutrophication	Water pollution Ecotoxicity (soil) – Not measured
	Ecotoxicity	
	Human toxicity	Not measured
Resource criteria	Resource depletion due to energy consumption	Not measured
	Mineral resource depletion	Not measured
	Water consumption	Water use
	Land use	Land use
Social criteria	Vehicle safety	Not measured
	Congestion	Not measured
	Noise and vibration	Not measured
	Vehicle interior air quality	Not measured
	Mobility capability	Measured in customised TIMM
	Employment quantity	Employment tax
	Occupational health and safety	Health and Safety – JLR Supply chain - Not measured
	Labour rights	Not measured
	Human rights	Not measured
Economic criteria	Life cycle cost	Corporate economic performance

5.2. Refining and prioritising project deliverables and objectives

Monetisation of all twelve areas identified in the comparison was too ambitious for this EngD to deliver. Methodological developments for these areas were not as far advanced as for other impacts (e.g. global warming, acidification, photochemical ozone creation, land and water use). In fact, a full IPA for each of these twelve criteria could be a topic for separate doctorate projects. For these reasons, a scoping exercise was undertaken in **submission 3B** in order to select the priority assessment criteria and deliverables for this EngD project. The following two factors were considered in the scoping process:

- **Data available from the sponsoring company -** valuation methods needed testing based on real-world data from the automotive sector.
- **The methodological developments reported in the literature –** the literature review was essential to identify knowledge gaps.

5.2.1. Data available from the sponsoring company

Most of the required environmental and resource data were available from the JLR Sustainability Engineering team, with the exception of stratospheric ozone depletion which was not measured by JLR. A gap in the available data also possessed a potential problem for human and ecotoxicity. Although the JLR Sustainability Engineering Attribute team had the capabilities to produce this data with the help of GaBi LCA software, the reliability and quality of the data are low (EC-JRC, 2011; Hauschild et al., 2013). Resource data for this project were also available from the Sustainability Engineering Attribute team.

The social data required for this project were distributed across different business units within JLR, not all of which were prepared to participate in this EngD project. Furthermore, the valuation of certain social impacts (e.g. accidents, injuries and human health impacts) is problematic for JLR from an ethical point of view. History has demonstrated (see Birsch and Fielder, 1994) how taking an economic efficiency approach to justify product decisions without due consideration of ethics can expose a business to a number of lawsuits and extremely bad publicity. Hence, the Vehicle Safety Attribute and NVH departments at JLR refused to share their data for the purpose of this project. It was also not feasible to obtain input from JLR engineers working on autonomous driving systems. Data for the remaining social impact categories were available although they remained incomplete. For example, employment quantity and quality data were specific to JLR and neither upstream nor downstream effects were considered.

5.2.2. Methodological developments reported in the literature

Reliable and credible source of damage cost estimates for twelve areas in the A-SAM for which PwC could not deliver value were rarely available in the literature. The best contribution with regard to valuation methods and coefficients of the global impacts of resource depletion comes from the LCA field of research, including the ReCiPe (Goedkoop et al., 2008) and LC-IMPACT (Ponsioen et al., 2014, Vieira et al., 2016) projects. Both ReCiPe and LC-IMPACT assess the impact on resource scarcity based on the surplus cost concept, defined as a global future cost increase due to marginal resource use (Ponsioen et al., 2014). Currently, quality surplus cost estimates for minerals other than fossils are either not yet available or have methodological and data limitations (West, 2011, Drielsma et al., 2016, Vieira et al., 2016).

Estimates of the marginal cost of accidents, congestion and noise caused by passenger cars can be found in the EC IMPACT project (Maibach et al., 2008; Korzhenevych et al., 2014). These estimates were derived in the context of transportation systems in general and they measure the additional costs of accidents, congestion and noise caused by adding one more vehicle to the existing traffic flow (Maibach et al., 2008). Hence, these estimates are potentially practical for decision-making at the policy level but not necessarily at the organisational level. They would have to be investigated in the context of the specific vehicles and technology they were applied in order to be practical for automotive organisations.

5.3. Final recommendations

Table 6 summarises the results of the scoping exercise. The optimum decision for the scoping of this project was to focus primarily on those areas in Table 6 for which quality data were available from JLR (**green cells in column 1**) and valuation coefficients were not or were only partly available in the literature **(red or orange cells in column 2)**, to enable the project to contribute to scientific knowledge. Following this line of thought, the optimum areas of this project for examination in the first place were:

- **Resource depletion due to energy consumption;**
- **Mineral resource depletion; and,**
- **Vehicle interior air quality.**

The results of this analysis were further discussed with the JLR Sustainability Engineering Attribute team to guarantee the maintenance the academic rigour, novelty as well as industrial relevance of the results obtained. JLR confirmed these areas, in addition to human and ecotoxicity, as top priorities for the company. The issue with human and ecotoxicity is the lack of quality data that could be provided by JLR.

Technological improvements and regulations over recent years have focused on the reduction of tailpipe emissions as a top priority (Jasinski et al., 2015). As a result, responsible material use has the potential to grow proportionally to become a major source of environmental impacts across the lifetime of a vehicle (Mayyas et al., 2013). Hence, resource depletion was selected as the primary area of focus in this EngD project. If time allowed, vehicle interior air quality was the next priority.

Table 6 The process of prioritising twelve areas in the A-SAM for which PwC could not deliver value

Sustainability category	Assessment criteria	Measured by JLR/Available for EngD	Coefficients available in the literature
Environmental impact	Stratospheric ozone depletion	No	No
	Human toxicity	No/can produce (CML 2001)	No
	Ecotoxicity	No/can produce (CML 2001)	No
Resource impact	Resource depletion due to energy consumption	Yes/Yes	Partly (depending on the method and minerals)
	Mineral resource depletion	Yes/Yes	Partly (depending on the method and minerals)
Social impact	Vehicle safety	Yes/No	Partly (marginal accident cost estimates)
	Impact on congestion	Partly (autonomous driving)/No	Partly (marginal congestion cost estimates)
	Noise and vibration	Yes/No	Partly (marginal noise cost)
	Vehicle interior air quality	Yes/Yes	No
	Occupational health and safety	Partly (JLR only)/Yes	No
	Labour rights	Partly (JLR only)/Yes	No
	Human rights	Partly (JLR only)/Yes	No

Data available — Data available but either incomplete or additional work is required — Data not available

The next section of this Innovation Report demonstrates the research approach and methods used for the measurement and valuation of resource depletion impacts based on the input data obtained from JLR.

6. A comprehensive approach to resource depletion impact assessment

Literature reviews conducted in **submissions 4 and 5** suggested three different types of resource depletion impact modelling (see Figure 12). Each model looks into different time frames and provides different but complementary information about the consequences of resource depletion.

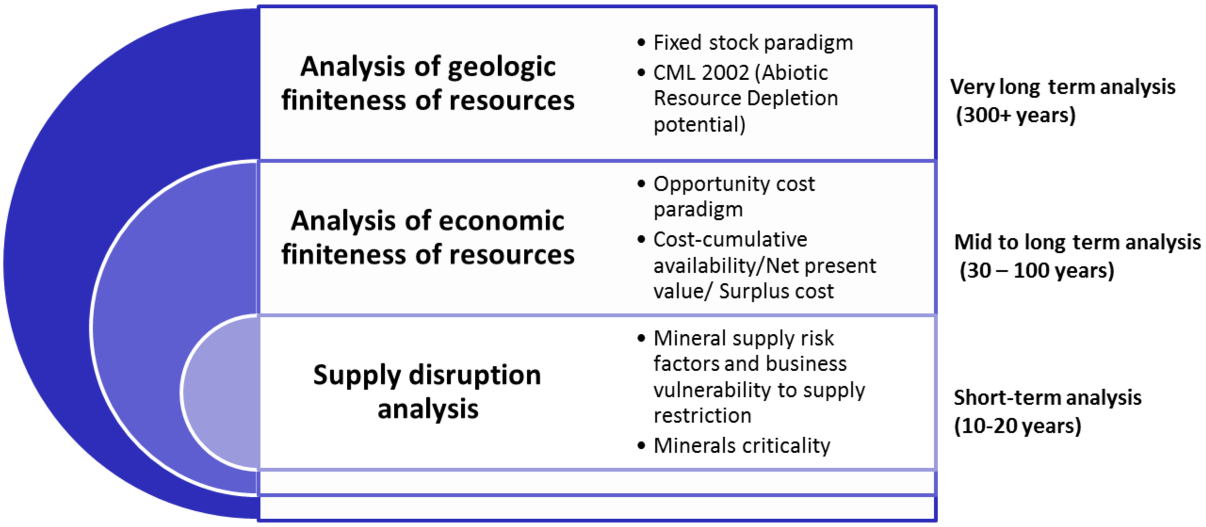

Fig. 12 Three levels of resource depletion analysis (adapted from: Drielsma et al., 2016).

An analysis of geological finiteness of resources – the fixed stock model is based on the assumption that the Earth is finite, and that fixed amounts of minerals are therefore contained within the planetary boundaries. This fixed stock is reduced as more minerals are mined and may eventually disappear in the future (Humphreys, 2013). In this approach, exhaustion of the resource itself is considered the key problem, with no distinction between or valuation of the resource's potential functions for mankind (Van Oers et al., 2002). The most widely accepted method of measuring resource depletion under the fixed stock paradigm is the Abiotic Resource Depletion Potential (ADP) indicator (Guinée, 1995, Van Oers et al., 2002). The ADP indicator estimates the decreasing availability of resource stocks based on the ratio between the extraction rate and the squared geological stock of a resource normalised to the reference substance antimony (Guinée, 1995, Van Oers et al., 2002).

An analysis of economic finiteness of resources – the opportunity cost models assesses the sacrifice that society has to make in order to obtain an additional quantity of a given resource, such as higher energy requirements and the change in future marginal extraction costs resulting from the combination of depletion, exploration results and cost-reducing innovation (Steen, 1999, Goedkoop et al., 2008, Ponsioen et al., 2014). In this approach, the area of protection is not a resource's intrinsic value, but rather the functions it may potentially fulfil for society both now and in the future. The increasing cost of resources is thus becoming a major problem for society, not merely their physical availability (Meadows et al., 2004). Rather, it is more likely that the rising costs of extracting a mineral such as copper from the Earth will eradicate demand for it a long time prior to exhaustion of the physical resource itself (Tilton and Lagos, 2007, Humphreys, 2013). For this reason, a function of the long-run costs and prices of minerals provides a more promising early warning indicator of impending resource scarcity than do measures related to their physical availability (Yaksic and Tilton, 2009, Humphreys, 2013, Drielsma et al., 2016).

Supply disruption analysis – fixed stock and opportunity cost models focus exclusively on the mid- to long-term geologic and economic finiteness of resources. They ignore other technological, geopolitical, regulatory and social risk factors (e.g. wars, market imbalances, governmental interventions or restrictions to mining due to environmental degradation) that may lead to supply disruptions and increasing commodity prices in the short term (10 to 20 years) (Erdmann and Graedel, 2011, Schneider et al., 2014, Drielsma et al., 2016). Consideration of these additional risk factors in the evaluation of resource depletion impacts has recently emerged as a new research field and is known as 'minerals criticality assessment' (Helbig et al., 2016, Drielsma et al., 2016). The EC classes a raw material as critical when it faces high risks with regard to access to it, e.g. high supply risk or high environmental risks, and it is of high economic importance (EC, 2010). This definition of raw material criticality is an abstraction of classical quantitative risk assessment and is widely used in numerous disciplines such as safety engineering, climate risk management and project risk management.(Glöser et al., 2015).

At the time of conducting this research, JLR was utilising the fixed stock approach, which alone has a very little value for business decision-making considering very long time frames of the analysis and that the ADP indicator is not widely understood by decision-makers (Tilton and Lagos, 2007, Drielsma et al., 2016). The opportunity cost method as well as supply disruption analysis express resource depletion in economic terms, which was more applicable in the context of understanding mineral demand and availability from an industry perspective (Drielsma et al., 2016), and was in line with the FCA approach. Hence, both concepts were tested in this EngD based on minerals currently used in automotive manufacturing.

6.1. Mineral resources used in automotive manufacturing

A list of materials, minerals and mineral groups used in automotive manufacturing was elucidated based on an analysis of the bill of materials (BOM) for the Range Rover diesel hybrid, the most complex car in the JLR range. A typical BOM for a vehicle consists of approximately 1800 entries in a Microsoft Excel spreadsheet. To simplify the analysis, the BOM was aggregated to 14 minerals and mineral groups, with metals and metalloids accounting for nearly 71.7%, thermoplastics 14.8%, elastomers nearly 4.9%, ceramic and glass 3.6%, natural materials nearly 1% and other materials 4% of the total mass of a vehicle, as summarised in Table 7.

Table 7 The proportion of materials in a vehicle by mass (JLR data)

Material	Vehicle content by mass (%)
Steel	37.52
Aluminium (Al)	25.12
Thermoplastics (oil)	14.80
Iron (Fe)	5.77
Elastomers (oil, natural rubber)	4.87
Ceramics/glass	3.65
Copper (Cu)	1.86
Natural materials (e.g. wood, leather, cardboard)	0.96
Magnesium (Mg)	0.54
Lead (Pb)	0.53
Zinc (Zn)	0.26
Rare metals (e.g. gold, Platinum Group Metals (PGMs), Rare Earth Elements (REEs))	0.10
Nickel (Ni)	0.01
Other (lacquers, lubricants, electronics, HEV components).	4.01

Time and resources available to this EngD project did not allow to conduct a full opportunity cost modelling for all minerals identified from the BOM. Data collection for a single mineral could take from three months (as was in this project) to over a year (Yaksic and Tilton, 2009). Instead, a set of sample minerals was selected to test the opportunity cost concepts and supply JLR with the internal capabilities and tools required to conduct a more detailed analysis in the future.

Looking solely at the vehicle mass content of each mineral Fe (including steel), Al and thermoplastics (oil) seemed the most relevant for the automotive sector and were obvious candidates for use in testing the opportunity cost approach. However, Tilton (2003) proved the Earth's crust contains prodigious amounts of Fe and Al and therefore these minerals are very unlikely to see significant increases in cost as a result of their increased extraction. Furthermore, the global average recycling rates for Fe and Al are high (above 50%), with recycled content between 25% and 50% (Reuter et al., 2005, Graedel et al., 2011a), thereby reducing demand for primary mineral production. The study of Aguilera et al. (2009) indicated that petroleum resources used to make thermoplastics are likely to last far longer than many are predicting and that depletion should not drive market prices above the relatively high levels prevailing over recent years.

Those minerals reported as rare and potentially scarce (e.g. europium, yttrium, gallium, indium and the PGMs) (EC, 2014) are exposed to higher risk of deficit and are therefore more likely to become an issue for the automotive sector in the future. For this reason, they were better candidates for use in testing the opportunity cost approach. The metals selected in this study were platinum, palladium, rhodium, ruthenium and iridium, all of which are PGMs. PGMs are the primary metals utilised in catalytic converters in both diesel and gasoline engines (Johnson Matthey, 2013b). Aside from the fact that they are rare, these metals were also selected for the following reasons:

- there are currently no substitutes to replace PGMs in autocatalysts (Chapman et al., 2013, Tercero Espinoza et al., 2015). Since internal combustion engines remain dominant in car manufacturing, any increases in costs of PGMs may have severe consequences for JLR’s revenue and profit.
- the automotive sector is both a major consumer of PGMs and a major contributor to their depletion, accounting for over 40 per cent of annual gross demand (Johnson Matthey, 2013b); and,
- PGM deposits and production are concentrated in a small number of countries (Johnson Matthey, 2013b), thereby facilitating the data collection process.

The results for PGMs were compared with those for lithium. Lithium is a potential substitute for PGMs in future automotive applications, depending on the rate and extent to which electric cars replace cars with internal combustion engines. Li-ion batteries have been proven to be efficient on-board energy storage systems in hybrid electric vehicles (HEVs) (Aditya and Ferdowsi, 2008, Young et al., 2013).

The sample minerals selected for supply disruption analysis were all (thirty-one in total) metals and metalloids used in automotive manufacturing. The analysis of a small group of minerals has limited benefit for the business decision-making as the criticality value assigned to an individual material with a specific indicator weighting is of only limited informative value for a person charged with making decisions (Glöser et al., 2015). For this reason, it made sense to incorporate the whole range of metals and minerals in the assessment (Schneider et al., 2014).

6.2. Model 1: the opportunity cost approach

A surplus cost potential indicator, classified under the umbrella of opportunity cost methods, measures the net present value of the increase in mineral production costs associated with each additional extraction of a mineral commodity (Steen, 1999, Goedkoop et al., 2008, Vieira et al., 2012, Ponsioen et al., 2014, Vieira et al., 2016). The uniqueness and strength of this method lie in its ability to model resources that are produced as co-products by using a system of price allocation. Many minerals are almost exclusively mined as co-products of other metals (e.g. rhodium, ruthenium, iridium and rare earth elements), and surplus cost more closely resembles the real world than other methods that address only the depletion of single minerals (EC-JRC, 2011; Hauschild et al., 2013) (see **Submission 4** for the review of opportunity cost methods). Surplus cost was selected by the EC-JRC (EC-JRC, 2011) as showing promise and as the best of the existing measures available for capturing resource depletion at the end-point level, although it is not yet considered sufficiently mature for recommendation.

For example, the method has been criticised by relevant organisations in the metals and minerals mining sector (e.g. the European Association of Mining Industries, the Nickel Institute and the European Copper Institute) for utilisation and linking of the ore grade decrease function with the increasing marginal extraction cost of metals (see Drielsma et al., 2016). Factors other than ore grades affect the cost of mineral extraction (e.g. mine type, new discoveries, labour cost and technological developments). Furthermore, production cost data pertaining to minerals are much more difficult to obtain than, for example, geological data (Yaksic and Tilton, 2009). Existing surplus cost studies for metals used a simplified approach by assuming constant mining costs across all mines (see Goedkoop et al. (2008). Vieira et al. (2016) adjusted surplus cost estimates for 12 metals by using actual cost data purchased from commercial database World Mine Cost Data Exchange. However, these data do not recognise the characteristics of different deposits and mining technologies. Also, these data are not publicly available, and it is therefore not possible to reproduce and validate existing surplus cost estimates.

These limitations were overcome in **Submission 4**, which demonstrates how surplus cost estimates could be modelled without the utilisation of ore grade function and without the need to rely on authoritative institutions or purchase data from commercial databases.

6.3. Research approach

The surplus cost potential indicator (SC_x) is based on three parameters (Ponsioen et al., 2014), as shown in Equations 1 and 2:

$$SC_x = \sum_{t=1}^{T} (MCI_x * P_{x,t} * \frac{1}{(1+d)^t}) \qquad \textbf{(Eq. 1)}$$

where,

$$MCI_x = \frac{\Delta Cost_x}{\Delta P_x} \qquad \textbf{(Eq. 2)}$$

MCI_x is the marginal cost increase of mineral x expressed as a ratio of the change in the cost per kilogram of mineral x ($\Delta Cost_x$) to the change in the amount to be produced in the future (ΔP_x). $P_{x,t}$ is the annual production of mineral x in year t counting from the base year, T is the year in which the considered mineral resource *x* is depleted and *d* is the discount rate. The process of modelling and estimating these parameters is explained in the following subsections.

6.3.1. The construction of cost–cumulative availability curves

The MCI parameter was derived from the function of cumulative mineral production and changes in its production costs (Ponsioen et al., 2014). This required the construction of cost–cumulative availability curves which provide geological knowledge of existing mineral deposits, their sizes as well as the potential costs at which these deposits might be extracted. Data for constructing these curves were available for lithium (see Yaksic and Tilton, 2009) but not for PGMs. The construction of a cost-cumulative curve for PGMs was both time and resource intensive and it took approximately three months, between January and March 2016. The development process is explained as follows:

- **Phase 1** involved collecting and analysing data about the distribution of PGM deposits, mining companies and projects around the globe as well as data on deposit types, mine types, ore grades, total resources, production volumes and operational and capital costs for PGM mines and deposits. The best data for Phase 1 were collected from the US Geological Survey (USGS, 2014), British Geological Survey (BGS, 2009), Geoscience Australia (Hoatson et al., 2014), Natural Resources Canada (NRC, 2015), Geological Survey of Finland (online), Johnson Matthey (2013b), the Department of Mineral Resources in the Republic of South Africa (Moumakwa, 2014), the International Platinum Group Association and a number of annual, technical and production reports, press releases, investor presentations, feasibility studies and the official websites of PGM mining, exploration and consulting companies.

- **Phase 2** involved estimating a geological composition of PGMs depending on the deposit types. A typical deposit contains various metals but there is usually a main metal that justifies the exploration of a given deposit (Vieira et al., 2016). PGMs are mined as both the main and accompanying metals of Ni and Cu deposits (Hagelüken and Meskers, 2010). A general concentration of PGM elements was assumed based on the existing literature (Theart and De Nooy, 2001, Crundwell et al., 2011, Zientek et al., 2014) and the websites and reports of mining and exploration companies.
- **Phase 3** entailed the collection of annual operating costs (also called cash costs), capital expenditures and production volumes from a variety of sources (see the data collection section, Phase 1). Estimations of capital expenditures on an annual basis are more complicated than estimations of operational costs since capital expenditures are incurred largely at the start of mining, with additional irregular expenditures incurred during the ensuing years of the project. If the ultimate capital expenditures for the lifetime of the project are not known, the annual distribution of capital costs is best reflected by the depreciation of buildings and equipment (Aguilera et al., 2009). This approach was also adopted in this study. An accounting technique of joint and by-product costing based on sales values had to be applied in order to allocate total production costs to specific mining outputs (Drury, 2013). All costs were adjusted for inflation using the CPI inflation calculator available at the Bureau of Labor Statistics website and converted into US dollars for the year 2014 ($US2014).
- **Phase 4:** following the estimation of geological distribution and production costs, the cost–cumulative availability curve for PGM deposits and countries was then constructed following a process similar to that used by Yaksic and Tilton (2009) for lithium. For each deposit, a minimum and maximum production cost was selected based on the calculated total costs per unit produced. This selection of minima and maxima allowed

for the capture of the dynamics and uncertainties associated with the potential fluctuation of PGM production costs in the future. It also allowed for the inclusion in the curve of those known projects (deposits) for which production costs could not be calculated, assuming they had the potential to be mined within the cost range estimated for other deposits in the country that had similar geological configurations, geographical locations and socio-economic situations. The cost–cumulative availability curve was created by ordering PGM deposits based on their minimum production costs, from lowest to highest, and adding together the amount of PGMs available within each deposit.

A similar curve for deposit type and country was constructed for lithium based on data published by Yaksic and Tilton (2009).

6.3.2. Modelling the MCI parameter

In order to develop a cumulative production slope representing the MCI parameter from the minimum and maximum costs per deposit type of PGMs and lithium, Ponsioen et al. (2014) proposed a statistical Monte Carlo technique, a simulation method that relies on repeated multiple and random trials and statistical analysis to determine the expected value from a probable distribution of values (Barreto and Howland, 2005, Raychaudhuri, 2008, Korn et al., 2010). Assuming that the mineral production cost per deposit is a random number between the minima and maxima, the Monte Carlo method enables the expected value to be generated to a specified level of certainty. There are a number of different software packages for use with the Monte Carlo method, but Monte Carlo simulations can also be performed using Microsoft Excel spreadsheets (Barreto and Howland, 2005, Raychaudhuri, 2008), as was the case in this study. The process employed in running Monte Carlo simulations was as follows:

- The total resources (including proved and probable reserves and measured, indicated and inferred mineral resources) available for each mineral were divided into equal production intervals for each mineral; respectively 10,000 kg for platinum, 10,000 kg for palladium, 5,000 kg for ruthenium, 1,200 kg for rhodium, 1,000 kg for iridium and 2E+10 kg for lithium from oceans and 2E+7 kg for other lithium deposits.
- A range of production costs was allocated to each interval based on the cumulative availability and production cost per deposit.
- Assuming a uniform distribution of production costs between the minima and maxima, random values for each production interval were generated using the *RAND()* function in Excel.
- In order to obtain an accurate value, the Monte Carlo method is based on a large number of simulations. The higher the number of simulations, the more accurate the results that can be obtained; however, the number of simulations is not that critical provided confidence bounds are also computed (Korn et al., 2010). Similar to the process used by Ponsioen et al. (2014), 10,000 simulations were run for each production interval, the minimum for industry standards (Field, 2009).

Cost values obtained from the Monte Carlo simulations were ordered from lowest to highest and the cost–cumulative production curve was developed with the range for each production interval and the mean slope representing the MCI of each mineral. Further statistical analysis was conducted, including estimation of the median, standard deviation and confidence bounds in order to estimate the precision of the obtained values (Raychaudhuri, 2008).

6.3.3. *Future mineral production*

One of the challenges in estimating the surplus cost indicator is predicting how the production of a given mineral will change over time. Scenario analysis is a critical tool in the world of finance and economics and is used to determine and analyse events that may take place in the future (Ringland and Schwartz, 1998, Van der Heijden, 2011).

Three different scenarios for the future production of PGMs and lithium were developed. The conditions common to all three scenarios, such as future population and economic growth, demand for minerals from non-automotive uses and the recyclability and mineral loadings per vehicle, are summarised in Table 8.

A major factor set to influence demand for PGMs and lithium over the coming decades is the use of whichever energy source becomes dominant for road transport. For example, the automotive sector's use of PGMs should decline and demand for lithium increase if, or once, electric cars replace cars with internal combustion engines. On the other hand, current automotive fuel cells rely heavily on platinum-coated catalytic converters, meaning any penetration of fuel cell technology will have a severe impact on demand for PGMs, with one FCV requiring approximately 30 grams of platinum (Sun et al., 2011). The projected demand for light-duty vehicles (LDVs), medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) in three different energy technology penetration scenarios was based on two IEA reports; Energy Technology Perspectives (Taylor, 2010) and Technology Roadmap: Electric and Plug-in Hybrid Electric Vehicles (Tanaka, 2011). These projections are presented in Figure 13 and are explained as follows.

Table 8 PGM and lithium demand forecast assumptions to 2070

	Baseline scenario	**Blue map scenario**	**Blue map without FCVs scenario**	**References**
Time span, region	2070, global			(Taylor, 2010); (Tanaka, 2011); (Johnson Matthey, 2013b)
Economic conditions	Global gross domestic product grows by an average of 3.1%.			
Social conditions	The world's population will grow by an average of 0.7%, reaching 9.2 bn in 2050 and 10.5 bn in 2070.			
Automotive market	Annual vehicle catalyst and battery production will equal growth in the vehicle fleet (one catalyst and one battery per vehicle, in use for 160,000 km). Demand for LDVs will grow by an average of 2.5%, from 60.5 million in 2010 to 268 million in 2070 (see Figure 13 for demand projections). Demand for MDVs and HDVs will grow by an average of 2%, from 4.5 million in 2010 to 14.7 million in 2070 (see Figure 13 for demand projections).			
Other markets	Demand for PGMs from other sectors: • jewellery, chemical, electrical, glass, other: 1% growth until 2070. Demand for lithium from other sectors: • Secondary batteries (rechargeable and portable devices): 10% growth until 2020, 3% growth until 2050 and 1% growth after 2050; • Primary batteries (non-rechargeable devices): 5% growth until 2020, 3% growth until 2050 and 1% growth after 2050; • Lubricating greases: 3% growth until 2030, 1% after 2030; • Ceramic and glass: 2% growth until 2030, 0.5% after 2030; • Air conditioning: 3% growth until 2020, 1% after 2020; • Aluminium: 5% reduction until 2020, no consumption after 2020; • Others: 2% growth until 2020, 1% after 2020.			(Yaksic and Tilton, 2009); (Johnson Matthey, 2013a)
Recyclability	Recycling can reduce primary metal consumption through the use of secondary materials. There are two major measures of recyclability: recycling rate and recycled content. The recycling rate measures the amount of metal recycled from scrap. Recycled content is defined as the annual tonnage of material scrap consumed divided by tonnage of material produced,			(Yaksic and Tilton, 2009); (Graedel et al., 2011a); (Johnson Matthey,

	depending on how much scrap is available. Hence, material content is a better measure of recyclability if one wishes to understand primary metal consumption based on existing recycling rates. Even with a high recycling rate, the amount of recycled content can be low due to a low amount of available material scrap. For this reason, recycled content was used in this study as a measure of reduced primary metal consumption as a result of recycling activities. The recycled content of PGMs is between 10% and 50%, with an average of 24% between 2008 and 2013. The level of recycled content will grow by an average of 1.5% until it reaches 90%. The recycled content of lithium is currently below 1%. This is expected to grow with the increased use of Li-ion batteries in EVs and HVs. Growth is assumed at an average rate of 2.7% until the amount of recycled content reaches 80%.	2013a); (Schneider et al., 2014)
Mineral loadings per vehicle	PGM loading per vehicle is the average between the US and European emissions standards and is assumed to decrease over time. The average PGM loadings (grams per vehicle) for LDVs are as follows: • Petrol: 3.52 until 2030, 3.3 until 2050 and 2.64 after 2050 • Diesel: 7.25 until 2030, 6.9 until 2050 and 5.66 after 2050 • Hybrid/PHEVs: 2.7 until 2030, 2.6 until 2050 and 2.07 after 2050 • FCVs: 16 until 2030 and 8 after 2030 Larger engines require more PGMs, therefore average PGM loadings for MDVs and HDVs were doubled and are as follows: • Petrol: 7.03 until 2030, 6.6 until 2050 and 5.28 after 2050 • Diesel: 7.25 until 2030, 6.9 until 2050 and 5.66 after 2050 • Advanced biofuels/CTL/GTL/Natural gas: 5.38 until 2030, 5.1 until 2050 and 4.15 after 2050 Average lithium loading was assumed to be 140 g/KWh with EVs needing on average a 42 KW battery (60 KW for electric light trucks), PHEVs a 7.5 KW battery and hybrids a 1.2 KW battery.	(Bloxham, 2009); (Lowe et al., 2010); (Sun et al., 2011); (Goonan, 2012); (Cooper and Beecham, 2013); (Nguyen et al., 2014)

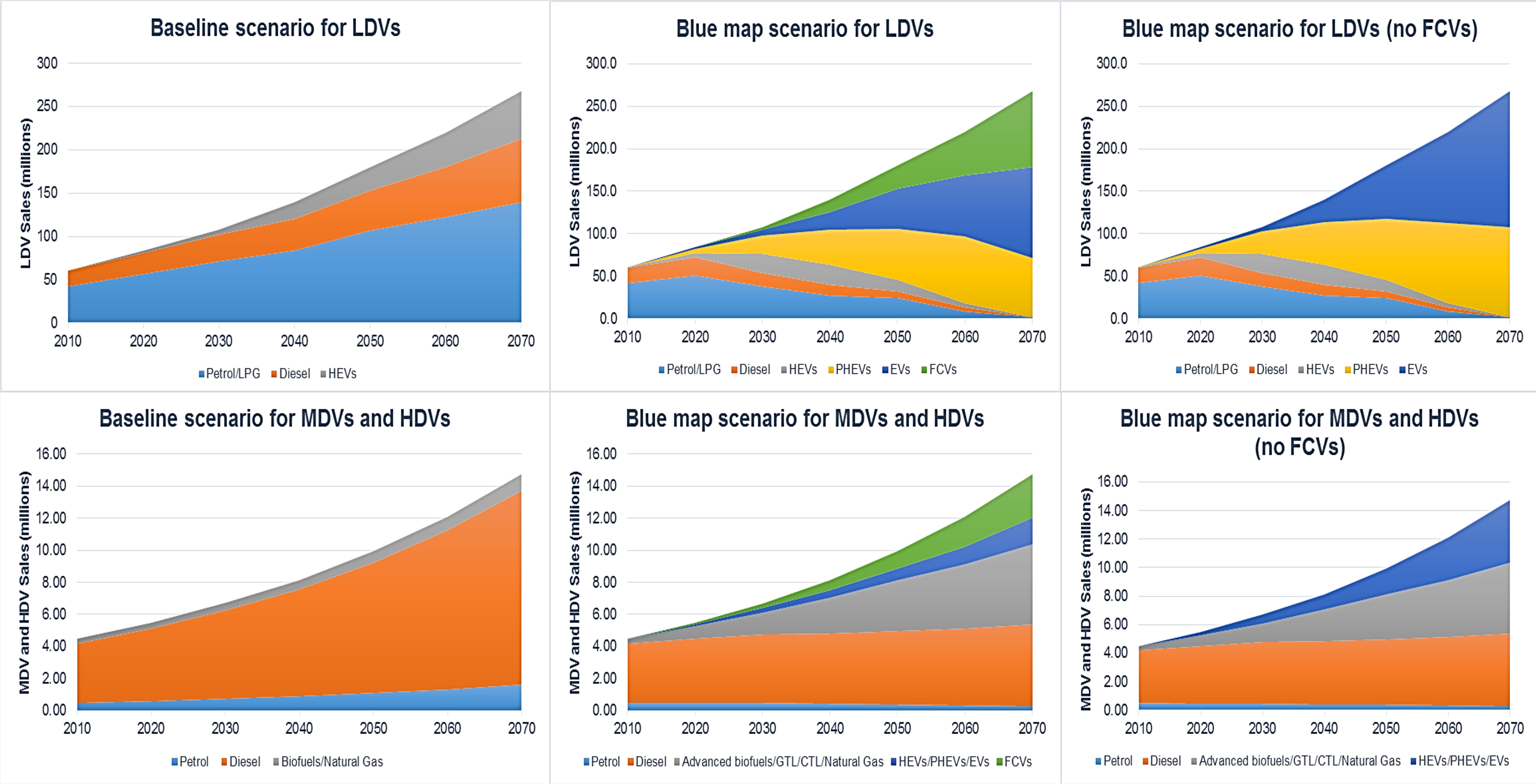

Fig. 13 Projections of future demand for vehicles in three different scenarios (adapted from: Taylor, 2010, Tanaka, 2011)

- **Scenario 1 (baseline):** in the baseline scenario, existing trends will continue and petrol and diesel vehicles will be dominant in the future with only a small proportion of hybrid vehicles (HVs) for LDVs and natural gas biofuels for MDVs and HGVs.
- **Scenario 2 (Blue map):** the Blue map scenario assumes a 50% global reduction in greenhouse gas (GHG) emissions by 2050 relative to their 2000 levels resulting from a strong mix of policy instruments focused on climate change. Obtaining the maximum efficiency gains in reducing GHG emissions will require a large penetration of plug-in hybrid electric vehicles (PHEVs), fully electric vehicles (EVs) and FCVs for LDVs. Electrification and fuel cells are also assumed for MDVs, along with an increase in the use of alternative fuels in HDVs, in particular advanced biofuels, gas-to-liquid, coal-to-liquid and natural gas.
- **Scenario 3 (Blue map without FCVs):** the third scenario is based on the same assumptions as Scenario 2, with the difference that the automotive sector will shift towards full electrification with no penetration of fuel cell technology. Hydrogen fuel cell systems have the potential to be a clean and efficient power option for vehicles, but there remain many technical and economic challenges that they must overcome prior to their full commercialisation (Sun et al., 2011).

6.3.4. Selecting a discount rate

The major assumption in the use of discount rates is that the value of one dollar today is greater than its value in the future. Hence, a discount rate is used to adjust the value of future revenue, costs or income flows in order to enable a comparison with the value of flows in the current period (UN System of Environmental-Economic Accounts, 2012). Following this line of thought, the future cost of mineral extraction in the surplus cost calculations needed to be discounted back to present-day values.

The issue with the selection of an appropriate discount rate is that it is based on value choices and is therefore subjective. Environmental economists are far from a consensus on which discount rate to apply (Khan and Greene, 2013). For example, Ponsioen et al. (2014) used three discount rates (0%, 3% and 15%) to estimate surplus cost for fossils. The original ReCiPe method used a 2%–5% range of discount rates (Goedkoop et al., 2008). The World Bank utilised a 4% discount rate to estimate natural capital in their wealth accounts (Jarvis et al., 2011). Wilmot, 2005

The UK Office for National Statistics recommends a third option of choosing a uniform 3.5% social discount rate, to be used for all types of natural assets regardless of the purpose of the exercise (Khan and Greene, 2013, Khan et al., 2014). This option was first outlined in HM Treasury's Green Book for use by UK authorities following consultation between experts and government officials. It has since been adopted by the French authorities and is also considered by US officials for all sustainability projects (Cropper et al., 2014). This option uses a declining uniform discount rate for impacts assessed over the very long term, at the rates presented in Table 9.

Table 9 Declining social discount rate proposed by HM Treasury (2003)

Number of years	0–30	31–75	76–125	126–200	201–300	300+
Discount rate	3.5%	3%	2.5%	2%	1.5%	1%

Declining long-term discount rates better represent the distribution of uncertain levels of economic growth into the distant future, or times when growth is unevenly distributed over time. Since natural resources are of long-term value to society, it made sense to use the declining social discount rate for the purpose of this modelling.

6.4. Results of the modelling

This section presents the cost-cumulative curves and surplus cost estimates for the PGMs and lithium.

6.4.1. Cost–cumulative availability of PGMs and lithium

PGMs occur in a wide variety of geological settings and are derived from several types of deposits, with two major deposit groups being platinum group element (PGE)-dominant deposits (Merensky, UG2, Platreef and the dunite pipes) and Ni-Cu-dominant deposits (see BGS, 2009). In PGE-dominant deposits, PGMs are the dominant economic components, with Ni and Cu as minor by-products. Ni-Cu-dominant deposits are the most important sources of Ni worldwide. Cu, Co, PGMs (primarily palladium), gold and sometimes Ag and Cr are mined as accompanying metals (BGS, 2009). Of the 65 PGM projects examined, the total cost per unit produced was estimated for 43. Based on these estimates, a minimum and maximum cost was allocated to each deposit and the cost–cumulative availability curve for PGMs was constructed as shown in Figure 14.

The underlying data used for construction of the CAC, including a list of known PGM deposits along with estimates of their quantities and production costs, are provided in Appendices 4 and 5 in **Submission 4.**

The production cost of PGMs from Ni-Cu-dominant deposits depends largely on the production costs and market values of Ni and Cu rather than the PGMs themselves. For example, an increase in the production costs and a decrease in the prices of Ni and Cu will shift the segment of the CAC pertaining to Ni-Cu-dominant deposits up despite there being no change or disruption to the PGM market. However, these deposits still make a significant contribution to the total availability of PGMs and were therefore included in Figure 14.

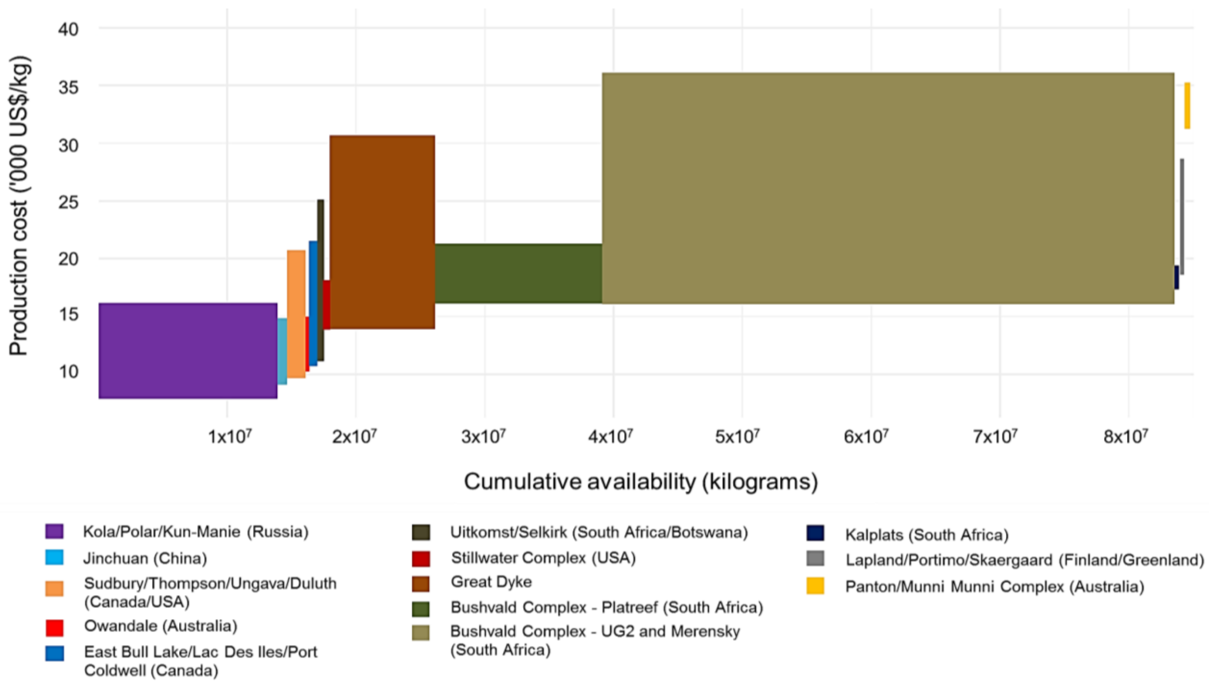

Fig. 14 Cost–cumulative availability of PGMs per deposit

To date, lithium has primarily been extracted, in all parts of the world, from two types of resources – brines and minerals (spodumene, lepidolite, petalite, amblygonite and eucryptite). Brines are currently the least expensive (no mining is required) and most relevant source of lithium. In addition to brines and mineral deposits, lithium can also be obtained from clays (hectorite) and seawater, both of which are potential future sources. Lithium, the same as PGMs, is mined both as a dominant metal (mainly from Li-rich pegmatites, which also contain other metals such as tin and beryllium) and as a by-product of other elements, mainly potash (K) (Nassar et al., 2015). The cost–cumulative availability of lithium is presented in Figure 15 and the underlying data used to construct the curve are given in Appendix 6 in **Submission 4**.

Figure 15 is incomplete as it contains only a small proportion of the lithium available from seawater (oceans). This is because the amount of lithium recoverable from the oceans is vast, 44.8 billion tonnes, and it was not possible to fit this into the graph with the lithium deposits. This does not pose a serious problem provided we keep in mind there is an almost infinite supply of lithium from seawater (see Appendix 6 in **Submission 4** for the specific amounts of lithium recoverable from each deposit).

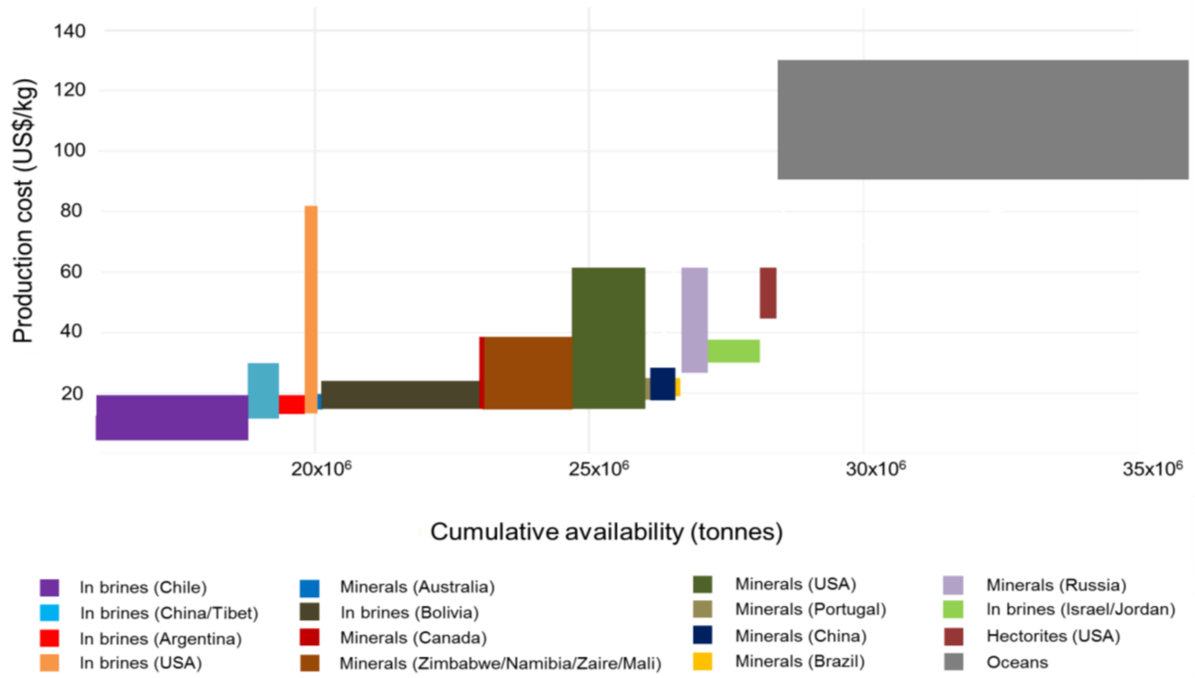

Fig. 15 Cost–cumulative availability of lithium per deposit

6.4.2. MCI results for PGMs and lithium

A statistical overview of the Monte Carlo simulations and MCI results obtained for each PGM and for lithium are presented in Table 10. The results represent the average MCI per mineral with 95% confidence bounds. The average difference between the mean and median for all metals is 0.45%, suggesting the data are normally distributed (Levin and Rubin, 2002). Individual cost–cumulative production curves for each metal, with the mean slopes and cost ranges per 10,000 kg of platinum, 10,000 kg of palladium, 5,000 kg of ruthenium, 1,200 kg of rhodium, 1,000 kg of iridium and 2*1010 kg of lithium from oceans and 2*107 kg from other deposits, are given in Figure 16. The slope for lithium is incomplete for the same reasons as in the case of the cost–cumulative availability graph. The cumulative production of each individual PGM was estimated based on the general concentration of PGM elements in different deposit types (see Appendix 1 in **Submission 4**).

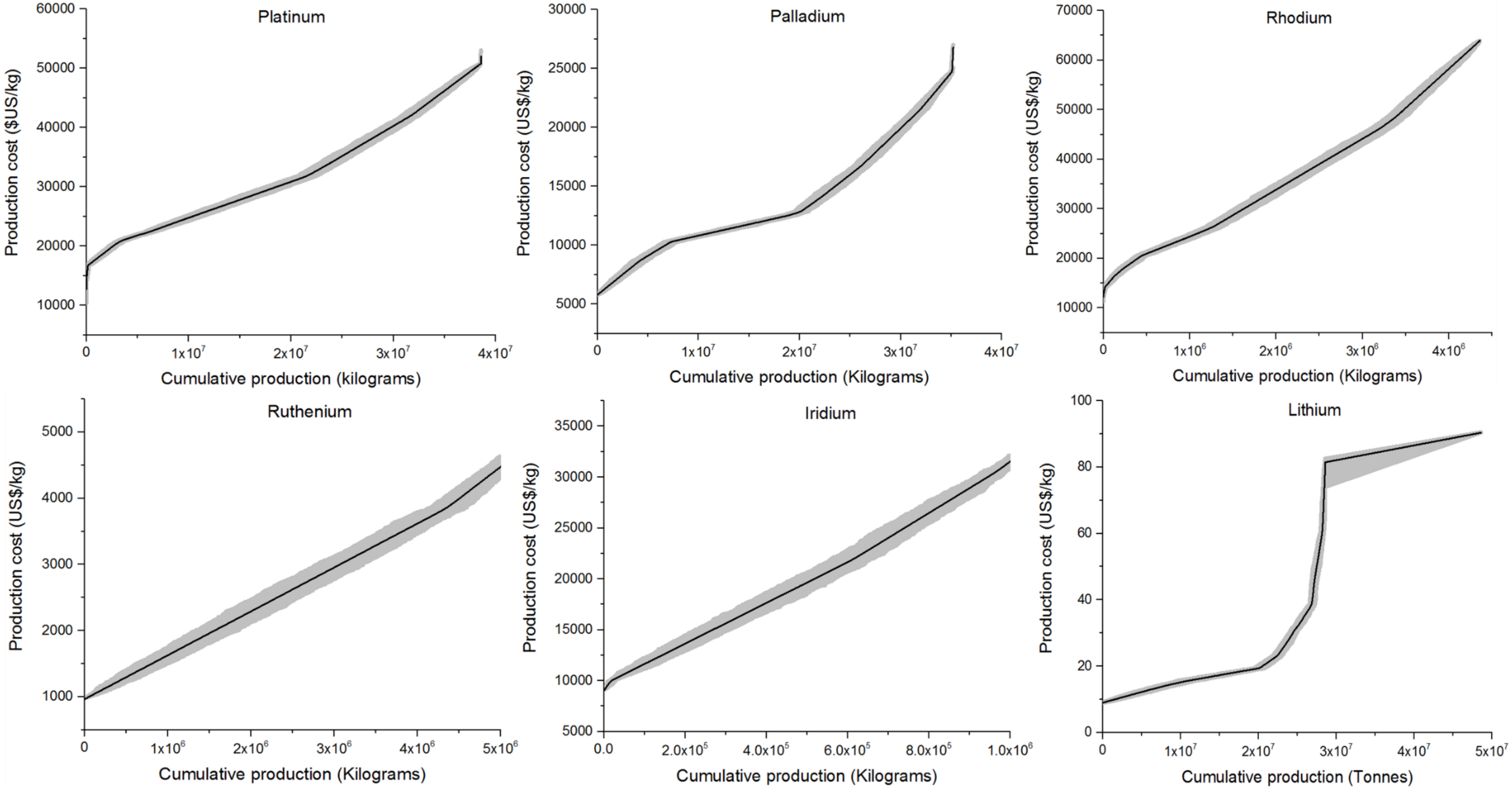

Fig. 16 Cost–cumulative production curves (mean slopes) for each mineral derived based on Monte Carlo simulations, with the grey area representing the cost range

Table 10 Average MCI calculations in US$ per kg of mineral produced

Metal	MCI ($US\$_{2014}$/kg)	Std. dev. ($US\$_{2014}$/kg)	95% confidence interval - lower boundary ($US\$_{2014}$/kg)	95% confidence interval - upper boundary ($US\$_{2014}$/kg)
Platinum	$1.019*10^{-3}$	$3.852*10^{-5}$	$9.434*10^{-4}$	$1.094*10^{-3}$
Palladium	$5.967*10^{-4}$	$5.889*10^{-6}$	$5.852*10^{-4}$	$6.082*10^{-4}$
Rhodium	$1.186*10^{-2}$	$1.144*10^{-4}$	$1.164*10^{-2}$	$1.208*10^{-2}$
Ruthenium	$7.344*10^{-4}$	$1.002*10^{-6}$	$7.325*10^{-4}$	$7.364*10^{-4}$
Iridium	$2.292*10^{-2}$	$6.344*10^{-5}$	$2.280*10^{-2}$	$2.305*10^{-2}$
Lithium	$1.116*10^{-9}$	$4.815*10^{-11}$	$1.022*10^{-9}$	$1.210*10^{-9}$

It is evident from Table 10 that the MCI estimates for the six metals are different, ranging from 2.292*10-2 for iridium to 1.116*10-9 for lithium. The reasons for this substantial difference are twofold. First, society places a higher value on PGMs than on lithium and is thus prepared to spend more to extract one kilogram of, for example, palladium than it is for the same quantity of lithium. Second, the available deposits of lithium are incomparably higher than for PGMs.

6.4.3. Surplus cost potential for PGMs and lithium

The cumulative supplies, estimated as in Sun et al. (2011) (mineral demand adjusted to mineral supply from recycling), of primary PGMs and lithium based on scenario analysis (up to 2070) are presented in Figure 17. These scenarios are somewhat optimistic, especially with regard to the rate at which the automotive sector shifts to full electrification and fuel cells.

As evident in Figure 17, the supply of primary PGMs by 2070 is greatest in Scenario 1, so in this case diesel and petrol vehicles will continue to be dominant in the future. In Scenarios 2 and 3, the supply of PGMs will slacken after 2030 as PHEVs and EVs begin to replace cars with internal combustions engines. EVs do not require the use of PGMs, while PHEVs need significantly smaller quantities than petrol or diesel cars (see Table 8). In Scenario 2, this trend will continue up to the point where FCVs become fully commercialised. With an increase in sales of FCVs, the supply of PGMs will increase at a higher rate than in Scenario 1, as these cars use more PGMs in their catalysts than internal combustion engines. Hence, after 2070, the cumulative supply of PGMs in Scenario 2 should exceed the supply in Scenario 1.

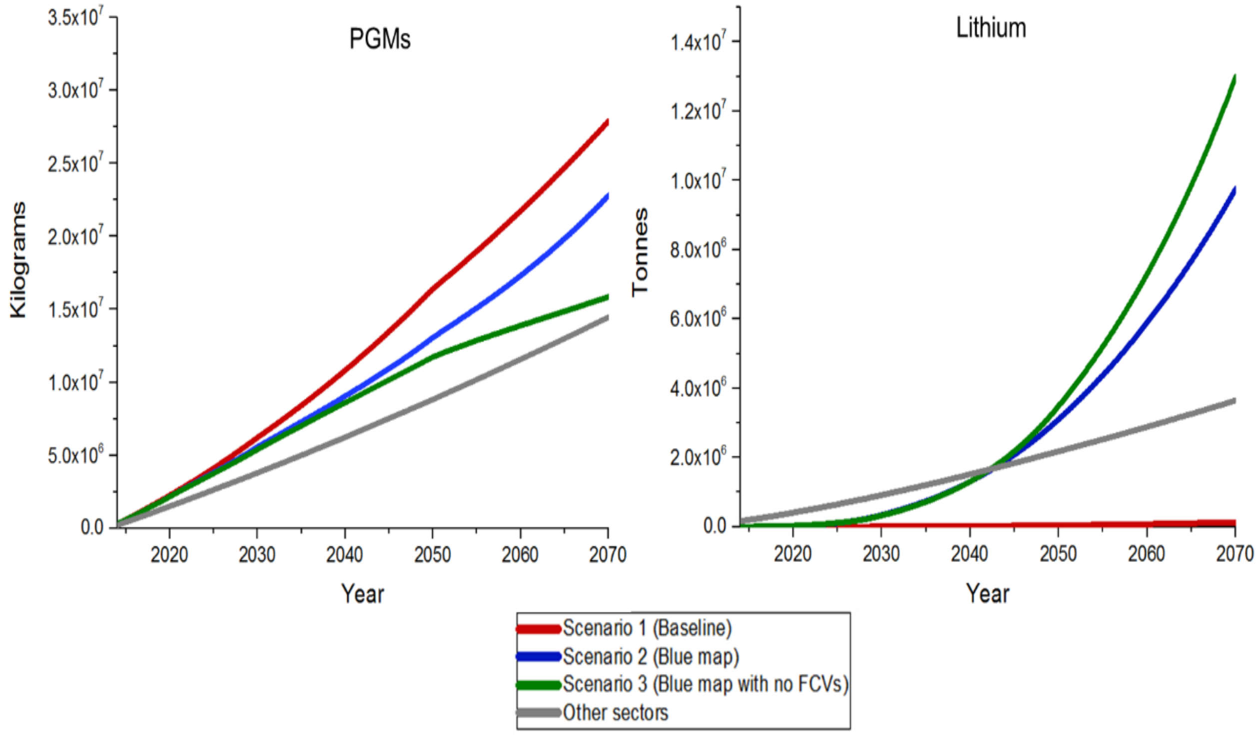

Fig. 17 Cumulative supply of primary PGMs and lithium

Scenario 3 assumes that no FCVs will be used in the future due to technological limitations. For this reason, the supply of PGMs in the automotive sector will systematically decrease as the world shifts towards full electrification. In fact, after 2070, the supply of PGMs in the automotive sector will be lower than for other sectors. The use of PGMs in the automotive sector will continue, albeit at a lower rate, mainly for MDVs and HDVs, which will themselves progress towards electrification at a much slower pace than LDVs.

The cumulative supply scenarios for primary lithium are expected to work conversely to those for PGMs. In Scenario 1, the supply of lithium for other sectors will grow at a faster rate than supply for the automotive sector as no electrification of vehicles is assumed. In Scenario 2, the supply of lithium will grow substantially by 2050 before weakening in line with increasing sales of FCVs. The rate of growth in the supply of lithium will be at its greatest in Scenario 3, once the road transport industry shifts to PHEVs and EVs.

Based on these future primary mineral supply scenarios, and by applying the decreasing discounting rate, surplus cost estimates were calculated for PGMs and lithium, as presented in Table 11. These estimates were supplemented with the current average production costs for PGMs and lithium to facilitate comparison.

Table 11 Surplus cost potential for each mineral in three different production scenarios compared with their current average production costs

	Surplus cost US$$_{2014}$/kg			Current average production costs US$$_{2014}$/kg
Metal	Scenario 1 (Baseline)	Scenario 2 (Blue map)	Scenario 3 (Blue map with no FCs)	
Platinum	8354	7428	6545	37859
Palladium	4573	4066	3583	19665
Rhodium	10569	9398	8281	31934
Ruthenium	655	583	513	1767
Iridium	4086	3633	3201	15129
Lithium	1.7	4.9	5.8	17.3

Supply levels for platinum, palladium, rhodium, ruthenium and iridium, as part of total supply of PGMs, were established based on historical data published by Johnson Matthey (2013a) (platinum, 46%; palladium, 43%; rhodium, 5%; ruthenium, 5%; iridium, 1%). These proportions can, of course, change, as only platinum, palladium and rhodium are currently used in autocatalysts and supply of these metals will grow at higher rate than of iridium and ruthenium. However, this assumption was made based on the fact that most PGMs are mined together and production of platinum and palladium currently determines maximum production of the others. Furthermore, ruthenium also has the potential to be used in catalysts, particularly in fuel cells (Albers et al., 2008).

Regardless of the scenario considered, PGMs have hundreds to thousands times higher surplus cost values than lithium. However, once compared with the current production costs, the differences between PGMs and lithium are not that significant, and they vary depends on the scenario considered. For example, surplus costs for ruthenium are about 37 (scenario 1), 33 (scenario 2) and 29 (scenario 3) per cent of the current production costs. These proportions for lithium work conversely to those for ruthenium and are as follow: 10 (scenario 1), 28 (scenario

2) and 34 per cent (scenario 3) of the current production costs. These results indicate that problematic price increases of lithium are unlikely if the latest technological trends in the automotive sector will continue up to 2070. Surplus costs for ruthenium are approximately one-third of the current production costs in all scenarios; hence, a threat of their price increases by 2070 will largely depend on the discovery of new deposits and the ability of new technologies to push these costs down over time. This also applies to lithium if the increasing electrification of road transport will continue up to 2070.

The surplus cost estimates provide a mid- to long-term outlook for the real threat of resource scarcity and the potential economic implications of their depletion. In the case of PGMs and lithium, the analysis comprised the period of fifty-six years. A supply disruption analysis (also known as minerals criticality assessment) has the ability to complement the surplus cost method with an analysis of potential risks of resource scarcity and increasing commodity prices in the short term (10 to 20 years) (Erdmann and Graedel, 2011, Schneider et al., 2014, Drielsma et al., 2016). The next section presents the research approach as well as results of raw materials criticality study conducted in **submission 5**.

6.5. Model 2: minerals criticality assessment

Minerals criticality assessment is system specific and typical critical minerals for the automotive business were yet to be defined. Despite relevant contributions from, for example, Yale University (Graedel et al., 2012, Nassar et al., 2012) and EC (EC, 2010, Chapman et al., 2013, EC, 2014), it remains a new area of research with no widely agreed methodology developed to date (Achzet and Helbig, 2013, Glöser et al., 2015).

Criticality assessments are inherently based on multiple criteria, which justified the use of multi-criteria decision aiding (also known as multi-criteria decision analysis, MCDA) for a consistent aggregation of criticality indicators into meaningful indices and to provide a comprehensive evaluation. MCDA is a process whose scope is to support decision makers (DMs) in structuring, understanding and solving a problem so that an informed decision can be recommended (Roy, 1996). It is emerging as a valuable strategy to carry out complex assessments due to its ability to effectively handle different types of information, include stakeholders' values and provide a transparent interpretation of the results (Cinelli et al., 2014, Balteiro-Dias et al., 2017).

In S**ubmission 5**, the synergistic use of ELimination and Choice Expressing REality (ELECTRE) MCDA methods based on algorithms for stochastic analysis (i.e. SMAA-TRI; Stochastic Multicriteria Acceptability Analysis for ELECTRE TRI) (Tervonen and Lahdelma, 2007) and optimisation (i.e. IRIS; Interactive Robustness analysis and parameters' Inference for multicriteria Sorting problems) (Dias et al., 2002) has been proposed to provide a classification system for the criticality of raw materials.

ELECTRE methods exhibit appealing advantages in comparison with other methods, these include weighted sum (the most frequently used MCDA method in minerals criticality studies): the weights of the criteria represent their 'voting power' and are independent of their measurement scales, are non-compensatory (they do not require trade-off rates), allow for the performance of sophisticated modelling through indifference, preference and veto thresholds that accounts for the hesitation of the decision-maker and the uncertainty in the information (not possible for the weighted sum and other MCDA methods) (Figueira et al., 2016).

Furthermore, the combinatoral use of SMAA-TRI and IRIS allowed to investigate the possible changes in results by accounting for the uncertainty of input parameters, in this case the weights of assessment criteria. Other ELECTRE-based methods need specific weight values (not available for this study), while SMAA-TRI and IRIS can operate without or with limited information about the weights of input parameters (assessment criteria).

The MCDA modelling was conducted in collaboration with Dr Marco Cinelli from Warwick Manufacturing Group and Warwick Institute for Advanced Study and Dr Luis Dias from Universidad de Coimbra, both of whom are experts in this research area. Their contributions and assistance were critical to ensuring methodological quality and soundness when using the MCDA methods.

6.6. Research approach

Following the classical definition of risk, the criticality assessment in this study was conducted using the dimensions of supply risk and economic impact. The construction of the supply risk index consisted of three steps: (1) the selection of a set of assessment criteria, (2) the assignment of indicators and criticality limits to each criterion based on industry best practice, (3) criteria weighting and aggregation into single risk-class profiles.

6.6.1. The selection of assessment criteria

A theoretical framework was first created to give a clear sense of what was being measured by the supply risk index. Graedel et al. (2012) distinguished six major elements that should be considered as part of a comprehensive evaluation of raw materials supply risk, as follows: geological, technological, economic, geopolitical, regulatory and social. These components were used to derive an initial draft of the supply risk index. Then, the supply risk assessment criteria, also known as impact categories, were identified based on a review of the existing raw materials criticality assessment studies (e.g. Achzet and Helbig, 2013, Schneider et al., 2014, Glöser et al., 2015). The identified criteria were then divided and organised into six supply risk components in line with the previously created theoretical framework. Finally, all criteria were assessed against four attributes to evaluate the suitability of a specific criterion for use in the overall supply risk index The attributes selected for use in this study were (OECD, 2008):

- **applicability** (the degree to which an indicator allows comparability of alternative options);
- **relevance** (the degree to which an indicator covers and contributes to the required topic and concept);
- **accessibility of the data** (the degree to which the data can be accessed for use); and
- **credibility of the data** (whether the data originate from or were produced by authoritative and credible institutions).

Table 12 compares all criteria against these four attributes, with an *X* indicating a negative assessment and a √ indicating a positive assessment of a criterion. Only those criteria which were assessed positively against all four attributes were considered in the construction of the supply risk composite index. The remaining criteria are either still immature, lacking in credible data or are not relevant in the context of what is being measured. For example, the geological availability measure is considered credible and is used by eleven criticality assessment studies but was dismissed by the EC as an inadequate indicator of raw materials criticality. The timescales associated with geological availability were deemed to be too long to have any relevant impact on the materials criticality assessment (EC, 2014).

Table 12 The initial framework of the supply risk composite index

Supply risk components	Supply risk impact categories	Potential source of data	Attributes sought			
			Applicability	Relevance	Accessibility	Credibility
Geological	Reserve availability	US Geological Survey (USGS) (USGS, 2016)	√	X	√	√
	Mine capacity utilisation	Various sources	X	X	X	X
Technological	Co-production	Yale University (Nassar et al., 2015)	√	√	√	√
	Recyclability	United Nations Environment Programme (UNEP) (Graedel et al., 2011a)	√	√	√	√
	Market substitutability	European Commision (Chapman et al., 2013)	√	√	√	√
Economic	Demand growth	European Commission (Chapman et al., 2013)	√	X	√	√
	Historic price volatility	USGS (USGS, 2016)	√	√	√	√
	Market balance	Various sources	X	√	X	X
	Minerals production cost	Various sources	X	√	X	X
	Investment in mining	Various sources	X	√	X	X
	Stock keeping	Various sources	X	√	X	X
Geopolitical	Global supply concentration	USGS for country concentration (USGS, 2016), no data for company concentration	√	√	√	√
	Governance stability	The World Bank (The World Bank, 2016)	√	√	√	√
	Import dependence	Local geological surveys or statistical agencies	X	√	X	√
	Climate change vulnerability	German Advisory Council on Climate Change (WBGU, 2007)	X	X	√	√
Regulatory	Environmental standards	Yale University (Hsu et al., 2016)	√	√	√	√
	Attractiveness of a country for exploration of resources (Policy Potential Index)	The Fraser Institute (Jackson and Green, 2015)	X	√	√	√
	Trade barriers	Various sources	X	√	X	X
Social	Subeconomic stability	United Nations Development Programme (UNDP) (Jahan et al., 2015)	√	√	√	√
	Press coverage – number of articles published	Various sources	X	X	X	X

6.6.2. *Supply risk indicators and discriminatory performance levels*

Assessment criteria are measured using indicators (Foxon et al., 2002), which, for this study, were determined for the eight selected criteria of recyclability, substitutability, co-production, historical price volatility, country concentration of production, governance stability, environmental standards and subeconomic stability. Furthermore, discriminatory ranges were defined to denote the supply risk levels for each indicator and thus the overall risk level for a mineral (Schneider et al., 2014, Glöser et al., 2015). Both the supply risk indicators and their accompanying rangess were determined based on best practice and recommendations from authoritative institutions and are summarised in Tables 13 and 14, respectively.

According to Table 13, classifications based on a single indicator use profiles to define intervals associated with risk levels. The most common case is to define four risk levels, ranging from high, high-medium medium-low to low risk. These four risk levels are also used in the multi-criteria classification models developed in this work, requiring to set ranges defining four classes on each remaining indicator (see Table 14). No reliable discriminatory ranges were found for the environmental standards indicator. To cope with this limitation, a four-point scale was built based on the percentiles of the distribution of the indicator across all countries (OECD, 2008). Based on this approach, the countries with the highest EPI (above the 75th percentile) received a low risk-class profile, those with an EPI between the 50th and 75th percentiles have a medium-low risk-class profile, an EPI between the 25th and 50th percentiles gives a high-medium risk-class profile and a country with an EPI below the 25th percentile received a high risk-class profile.

Table 13 Supply risk indicators recommended in the literature

Assessment criteria	Indicators	Description and thresholds
Recyclability	Recycled content	Recycled material has the potential to replace the primary supply of a mineral if this supply source is at risk (Chapman et al., 2013). Recycled content is a measure of recyclability if one wishes to understand primary metal consumption and is the annual tonnage of scrap material consumed divided by the tonnage of material produced (Schneider et al., 2014). Data and risk ranges for recycled content were sourced from the UNEP (Graedel et al., 2011a).
Substitutability	Substitutability Index	The risk of a disruption to the supply of a given mineral is reduced if reliable substitutes exist (EC, 2014). The EC was first to quantify this criterion by developing a substitutability index for a number of commodities and their end-use applications based on input from experts. The EC also provided risk ranges for this indicator on a scale of 0 (easily substitutable at zero cost) to 1 (not substitutable) (Chapman et al., 2013, EC, 2014, Tercero Espinoza et al., 2015).
Co-production	% of global primary production obtained as a companion	A co-product is a mineral derived during production of the main mineral and for which the elasticity of supply is directly limited by the extraction and processing of the base mineral (Achzet and Helbig, 2013). A quantitative assessment of minerals co-production in the form of a percentage of global primary production obtained as a companion, together with data and risk ranges, was recently released by Yale University (Nassar et al., 2015).
Historical price volatility	Standard deviation of changes in prices over time	Historical price volatility is a measure of the economic stability of a mineral obtained via analysis of its price changes over time. Producers of raw materials are sensitive to falls in price, which, in extreme cases, can lead to the closure of mines or refineries. Price volatility is calculated using the standard deviation of period-to-period changes in commodity prices and is commonly used by the EC in commodity price analysis (Chapman et al., 2013).
Country concentration (mine production)	Herfindahl-Hirschman Index (HHI)	Country concentration measures the supply risks associated with the production of a mineral being concentrated in a small number of countries (Erdmann and Graedel, 2011). The HHI is a widely accepted indicator of country concentration, calculated as the sum of the squares of market shares. HHI risk ranges can be found in the US Merger Guidelines released jointly by the US Federal Trade Commission and US Department of Justice and in the EU Merger Guidelines (EC, 2004, US Department of Justice and Federal Trade Commission, 2010).
Governance stability	World Governance Index (WGI)	Governance stability measures the political risk which may affect a mineral supply in the form of poor governance in mineral-producing countries (Chapman et al., 2013). Governance stability is captured in the minerals criticality literature mainly by the WGI developed by the World Bank (Achzet and Helbig, 2013). Risk ranges for the WGI were sourced from the Raw Materials Scoreboard report prepared by the EC-JRC (The World Bank, 2016, Vidal-Legaz et al., 2016).
Environmental standards	Environmental Performance Index (EPI)	The EPI developed by Yale University is the most widely accepted measure of the quality and effectiveness of environmental regulations in a given country. Producer countries with low environmental standards are exposed to a higher risk of accidents that lead to supply disruption than those countries with high environmental standards (Hsu et al., 2016). Although the EPI is recommended by the EC (Chapman et al., 2013), no credible risk ranges were found for this indicator.
Subeconomic stability	Human Development Index (HDI)	The HDI measures the level of a country's social progress in three areas of human development: health, education and living standards (Schneider et al., 2014). The inclusion of this measure in the study follows the rationale that as human development is likely to be improving in mining countries with a low level of social progress, the result may be new policies that influence mining activities in those countries. Countries with a high level of social progress usually already have restrictive social policies in place. Risk ranges for the HDI are provided by the UNDP (Jahan et al., 2015).

Table 14 Risk levels for supply criteria and indicators identified in the literature

Supply risk components	Assessment criteria	Indicator	High risk			Risk levels			Low risk	Min/Max values	Source of thresholds
Technological	Recyclability	Recycled content (%)	< 1% very low	1% – 10% low	11% – 25% medium	25% – 50% high	> 50% very high			0 – 100%	(Graedel et al., 2011a)
	Substitutability	Substitutability Index	1.0 not substitutable	0.7 substitutable at high cost or loss of performance	0.3 substitutable at low cost	0.0 easily substitutable at zero cost				0 – 1	(Chapman et al., 2013); (EC, 2014); (Tercero Espinoza et al., 2015)
	Co-production	% of global primary production obtained as a companion	> 75% very high	50% – 75% high	25% – 50% moderate	< 25% low				0 – 100%	(Nassar et al., 2015)
Economic	Historic price volatility	Standard deviation of changes in prices over time	> 0.47	0.40 – 0.47	0.32 – 0.40	0.24 – 0.32	0.16 – 0.24	0.08 – 0.16	< 0.08	0–infinity (1.58 very extreme)	(Chapman et al., 2013)
Geopolitical	Country concentration (production)	HHI	> 2500 > 2000 >1800 high concentration	2000 – 2500 1000 – 2000 1000 - 1800 moderate concentration	< 2000 < 1000 < 1000 not concentrated					0 – 10000	(EC, 2004); (US Department of Justice and Federal Trade Commission, 2010)
	Governance stability	WGI	-2.5 to -1.0	-1.0 to 0	0 to +1.0	+1.0 to +2.5				Governance score from -2.5 to +2.5	(Vidal-Legaz et al., 2016)
Regulatory	Environmental standards	EPI	No specific thresholds							Score 0 – 100	n/a
Social	Subeconomic stability	HDI	< 0.550 low	0.550 – 0.699 moderate	0.700 – 0.800 high	> 0.800 very high				0 – 1	(Jahan et al., 2015)

6.6.3. *Classification of minerals into supply risk profiles*

The identification of the overall supply risk of the minerals is difficult when looking at the performance on each criterion independently (see Figure 20). In fact, for each mineral, some criteria score well (or poorly) whereas some others do not and consequently it is not possible to define whether they can be assigned a high, medium-high, medium-low or low risk class.

In order to solve this challenge, MCDA methods were applied in this research as they can account for the performance of the minerals simultaneously and provide an integrated supply risk evaluation. The procedure for the selection of the MCDA methods and the respective outputs is presented in Figure 18. It included two phases which are briefly presented below.

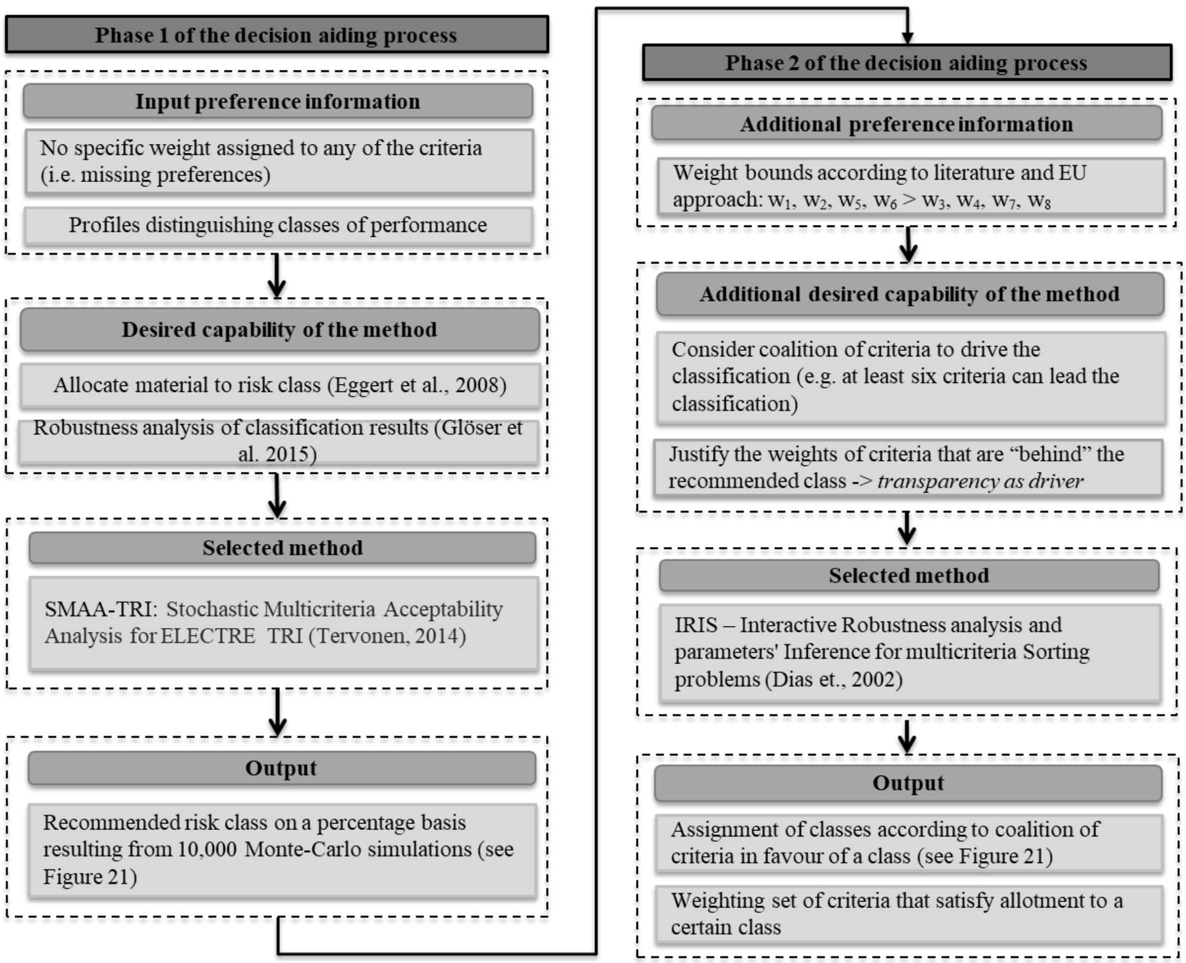

Fig. 18 The methodological procedure for the classification of minerals into supply risk classes

Phase 1 of the decision aiding process

Evaluation criteria are identified in a justifiable and traceable manner as described in Section 6.6.1, but their relative importance is not set in the relevant literature (unless assumptions are made as explained in Phase 2 below). Consequently, the MCDA method needs to be able to handle missing information on the weights of the criteria.

As described in Section 6.6.2, ranges of performance for allotment to a certain class were determined for each indicator, which implies the introduction of threshold values (i.e. profiles) distinguishing classes of performance (see Table 14).

Regarding the desired capability of the method, a robust classification to preference-ordered classes that takes into account the uncertainty in the input information has been a recurrent call in the literature (Achzet and Helbig 2013, Glöser et al., 2015).

As a consequence of these modelling needs, the most suitable MCDA method to emerge was SMAA-TRI (Tervonen et al., 2009b), which has already been used in decision-making problems with similar characteristics (Tervonen et al., 2009a, Cinelli et al., 2017). It is an approach based on an algorithm called ELECTRE TRI that allows for the assignment of raw material to risk class on a percentage basis resulting from 10,000 Monte-Carlo simulations of random criteria weights. Details on the SMAA-TRI working procedure can be found in Tervonen et al (2009) and Tervonen (2014).

Phase 2 of decision aiding process

The second modelling phase modified the preference information by adding constraints on the weights of the criteria. By accounting for the fact that an institution as authoritative as the EU decided to consider four (i.e. recyclability, substitutability, country concentration, governance stability) out of the eight criteria in their framework (EC, 2014). Consequently, the four criteria selected by the EU can be seen as having a higher importance than the others and thus higher weight, leading to the weights constraints w_1, w_2, w_5, w_6 > w_3, w_4, w_7, w_8 (see upper-right part of Figure 18).

The selection of the relevant MCDA method was refined by considering that DM can deem a certain minimum number of criteria (in this case 75%) as sufficient to grant a class, without requiring all the criteria to be in favour for it or a better one (Domingues et al., 2015). What is more, knowing the weights of the criteria that lead to a class represented another requirement for the identification of the method, as it can add transparency to the decision recommendation.

This modelling context resulted in the selection of IRIS as a suitable MCDA method (Dias and Mousseau, 2003). IRIS uses an optimisation-based algorithm to provide a range of risk classes together with the values of the criteria weights that drive each classification. IRIS operates with the ELECTRE TRI method as SMAA-TRI. Details on its working procedure can be found in Dias et al. (2002) and Dias and Mousseau (2003).

How does the classification algorithm work?

The models developed in this case study operate with an algorithm named ELECTRE-TRI (Roy, 1991), which sorts the raw materials into risk classes (C_i). This method compares the score for each criterion (g_j) with respect to class profiles (Pr_h), which distinguish between a high (C_1), high-medium (C_2), medium-low (C_3) and low (C_4) risk class (see Figure 19). Every C_i is defined by two profiles, a lower bound and an upper bound. For example, in the case of C_1 in Figure 19, Pr_0 is the lower bound profile and Pr_1 is the upper bound profile.

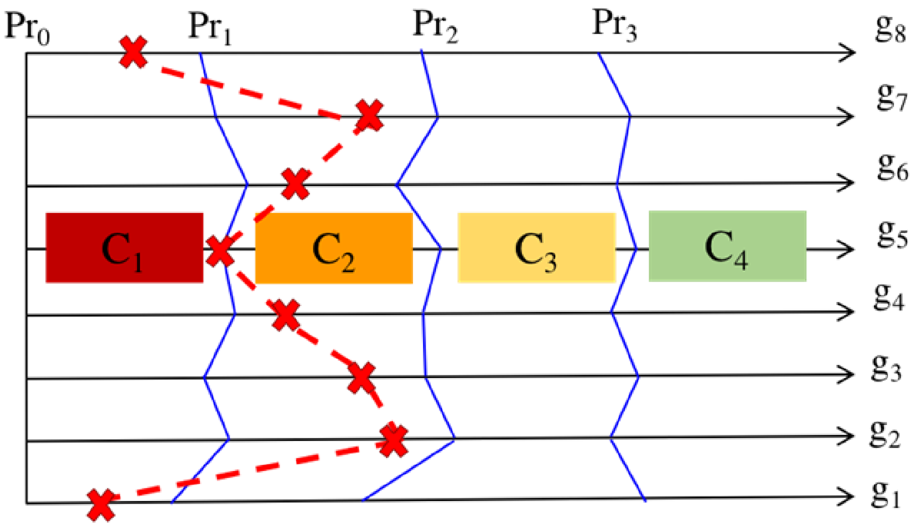

Fig. 19 Example of raw materials scoring in simplified ELECTE-TRI model (C_1 = high risk, C_2 = high-medium risk, C_2 = medium-low risk, and C_4 = low risk are a set of risk classes; Pr_h are risk class profiles; g_j are the criteria used in the classification; the direction of the arrows represents improved performance)

The performance of each criterion for every material is compared with the Pr_h from the worst to the best to evaluate whether such performance is at least as good as the profile (in MCDA terms the verb *outrank* is used). For each criterion in which the raw material equals or overcomes the Pr_h, the respective weight of the criterion is added to an index named concordance ($c(a_i, Pr_h)$). A threshold value denoted λ is used to drive the classification. Starting with h=1, if $c(a_i, Pr_h)$ (which can be also expressed as the cumulative weight of the criteria that equal or overcome the Pr_h) does not reach λ, the minimum cumulative weight of the criteria to grant a better classification, the raw material is allotted to class C_h (C_1 in Figure 19). If $c(a_i, Pr_h)$ reaches or exceeds λ,, the mineral can be assigned to a better class and it is compared with the next profile Pr_{h+1}. The process goes on until we reach a profile Pr_h such that $c(a_i, Pr_h)$ is lower than λ or when we reach the best class.

For instance, in Figure 19, criteria scores for g_2 to g_7 are at least as good as Pr_1, the upper profile of C_1. The sum of the weights of these agreeing criteria is $w_2+w_3+\ldots+w_7$. In case where $w_2+w_3+\ldots+w_7 < \lambda$ then the material belongs to class C_1, meaning that the criteria in support of C_2 are not enough to grant such class. In the opposite case, where $w_2+w_3+\ldots+w_7 \geq \lambda$, the raw material can be classified to C_2. As it clearly appears from this simple example, the classification procedure of ELECTRE-TRI is driven by the weight of the criteria that are in support of each C_i.

In order to account for the hesitation of DMs in face of uncertainty or imprecision in the values of the criteria and profiles, indifference and preference thresholds (Diaz-Balteiro et al. 2017) were used, which could be extrapolated from the available relevant literature (see Table 15. These account for the fact that the difference in performance between each criterion g_j and Pr_h can be considered insignificant if these performances are very close to each other. In practical terms, a criterion value slightly worse than Pr_h might still warrant the support (or the partial support) of that criterion to the hypothesis that the raw material outranks Pr_h.

Table 15 Scoring of indicators and associated risk level, indifference and preference thresholds extrapolated from the relevant literature

Indicators	Criteria scoring and associated risk level				Indifference thresholds (q_j)	Preference thresholds (p_j)	Uncertainty values for the classes profiles used to derive indifference and preference thresholds
	Low	**Medium**	**High**	**Very high**	$p_j = 2^* q_j$		
Recycled content (%)	> 50%	25 - 50%	10 - 25%	< 10%	**7.5**	15	Estimated error +- 5% (for RC 10%), +-7% (for RC 25%) and +-10% (for RC 50%).(Graedel et al., 2011b, Graedel et al., 2012)
Substitutability Index	0.0 - 0.3 easily substitutable at low cost, no loss of performance	0.4 - 0.6 substitutable at low cost but with loss of performance	0.7 - 0.9 hardly substitutable at high cost or loss of performance	1.0 not substitutable	**N/A**	N/A	Based on experts' input, no thresholds could be identified
% of global primary production obtained as companion	< 25%	25 - 50%	50 - 75%	> 75%	**7.5**	15	An average change of metals companionality over time was assumed to be 15% based on the two extreme examples of Molybdenium (28% change over 18 years) and silver (3% change over 14 years).(Nassar et al., 2015)
Standard deviation of changes in prices over time	< 0.16	0.16 - 0.28	0.28 - 0.40	> 0.40	**0.03**	0.06	The historical price volatility was estimated for each metal for the period of last ten years. Ten years is most relevant time period for the current technologies and end-markets for the raw material.(Chapman et al., 2013) The extension of this ten years period for another 5 years resulted in an average change of standard deviation across all metals by 0.06. This was used as the uncertainty value for the price volatility profiles if one wants to estimate the standard deviation of changes in prices over the 10-years period.
Herfindahl-Hirschman-Index (HHI)	< 1500	1500 - 2000	2000 - 2500	> 2500	**250**	500	The HHI classes profiles are moderately restrictive representing a compromise between the EU and US Merger Guidelines.(EC, 2004, US Department of Justice and Federal Trade Commission, 2010) The US Merger Guidelines are more rigorous with the HHI classes profiles lower for about 500 for each profile.
World Governance Index (WGI)	> 1	0 to 1	- 1 to 0	< - 1.0	**0.1**	0.2	An average standard error of the governance estimates calculated by the World Bank for 229 countries is 0.2.(Kaufmann et al., 2011, The World Bank, 2016)
Environmental Performance Index (EPI)	> 79	69.6 - 79	57.5 - 69.5	< 57.5	**4.3**	8.6	An average 10-year change of the EPI across 180 countries is 8.6.(Hsu et al., 2016)
Human Development Index (HDI)	> 0.800	0.700 - 0.800	0.550 - 0.699	< 0.550	**0.03**	0.06	An average 15-year change of the HDI across 188 countries is 0.06.(Jahan et al., 2015)

6.6.4. *Assessing the economic importance of raw materials*

The economic impact of a mineral supply disruption is highly dependent on the end use of the relevant mineral and needs to reflect the perspective of an individual economy, sector, company, community, region and so on (Achzet and Helbig, 2013, Dewulf et al., 2015). This criticality assessment modelling was performed to support decisions in the automotive context; hence, the economic impact assessment was conducted following consultation with and support from the Vehicle Sustainability Engineering team at JLR. This modelling concerned four major phases:

- **Phase 1:** seven economic impact measures applicable at the corporate level were distinguished based upon the literature review, as follows: substitutability, value of the products affected, strategic importance, value of utilised materials, ability to pass through cost increase, the target group's demand share and ability to innovate (see Appendix 1 in **submission 5** for the meaning of these measures).
- **Phase 2:** the measures were then discussed with the Vehicle Sustainability Engineering team at JLR. Four measures – strategic importance, ability to pass through cost increase, the target group's demand share and ability to innovate – were dismissed at this stage due mainly to their qualitative nature. The remaining metrics were considered important but with the need for further modification. While supply risk indicators evaluate the likelihood of a mineral supply disruption scenario, the potential scale of damage caused by such a scenario should be measured in monetary or strategic terms (Helbig et al., 2016).
- **Phase 3:** the economic impact measures and their severity class profiles were determined based on the best practice contained within the literature and by following

the recommendations from JLR. The business cost of a raw material supply disruption is usually measured in the form of potential economic losses (e.g. loss of revenue, sales or profits) arising from its temporary or permanent unavailability (Norrman and Jansson, 2004, Graedel et al., 2012, Shu et al., 2014). Hence, the economic impact of materials supply disruption in this study was measured in the form of lost gross profit either because a substitute is not available, and the company cannot sell a product line, or because a material needs to be replaced with a more expensive substitute that offers comparable performance. The four-point percentile scale used to measure the severity of the economic impact was sourced from Yale University's Methodology of Metal Criticality Determination (Graedel et al., 2012), with less than 0.5% of gross profit being low, from 0.5 – 2.5% medium-low, from 2.5 – 5% high-medium, and more than 5% high economic impact.

- **Phase 4:** the economic impact indicators and determined thresholds were presented to the Vehicle Sustainability Engineering department at JLR for final refinement on 17 June 2016. Apart from slight modifications and clarifications, no further changes were suggested by JLR. It was agreed and confirmed that the loss of gross profit needs to be assessed on the percentile scale as opposed to with actual values, as both the measure itself and its impact on the business will fluctuate over time.

6.7. Supply risk matrix and values

The supply risk matrix containing the eight supply risk assessment criteria and the risk-level profiles determined for each criterion is presented in Figure 20. A ‘high’ risk profile (red colour) indicates that a raw material performs extremely poorly in the corresponding (column) criterion and there is thus an increased risk of a supply disruption for this material. This dependence works conversely if a mineral is classified as being in a ‘low’ risk profile (green colour).

Thirty-one metals and metalloids used in automotive manufacturing were assessed against the supply risk matrix, with each mineral assigned a risk category according to its performance on each supply risk criterion (indicator). Figure 20 summarises the results for all thirty-one minerals and mineral groups by indicating the performance as well as the resultant risk category within each supply risk assessment criterion. In order to obtain a single HHI, WGI, EPI and HDI score for a particular mineral, the scores for each country were weight-averaged by the annual mining production of that country. This is in line with the approach proposed by Yale University and the EC (Graedel et al., 2012, EC, 2014). The underlying data behind the reported performance and production volumes for all raw materials can be found in Appendix 2 in **submission 5**.

The results in Figure 20 demonstrate that apart from, for example, REEs, Ta and Cu, there is large variability in the distribution of risk-level profiles across minerals. This complicates matters if the aim is to assign a single risk-level profile to a mineral based on all eight assessment criteria. The next section demonstrates the possibility of obtaining robust classifications of the materials in their risk-level profiles based on a synergistic use of SMAA-TRI and IRIS outranking methods.

Criteria / Risk level profiles	g_1 = Recyclability	g_2 = Substitutability	g_3 = Co-production	g_4 = Historical price volatility	g_5 = Country concentration	g_6 = Governance stability	g_7 = Environmental standards	g_8 = Subeconomic stability
	Recycled content	Substitutability index	% of global primary production obtained as a companion	Standard deviation of changes in prices	Herfindahl Hirschman-Index	World Governance Index	Environmental Performance Index	Human Development Index
C_1 = High risk	$g_1 \leq 10\%$	$g_2 = 1.0$ (not substitutable)	$g_3 > 75\%$	$g_4 > 0.40$	$g_5 > 2500$ (very high concentration)	$g_6 < -1.0$	$g_7 < 57.5$	$g_8 < 0.550$
C_2 = High-Medium risk	$10\% < g_1 < 25\%$	$0.7 \leq g_2 < 1$ (hardly substitutable at high cost or loss of performance)	$51\% < g_3 \leq 75\%$	$0.28 < g_4 \leq 0.40$	$2000 < g_5 \leq 2500$ (highly concentrated)	$-1.0 \leq g_6 < 0$	$57.5 \leq g_7 < 69.6$	$0.550 \leq g_8 < 0.700$
C_3 = Medium-Low risk	$25\% \leq g_1 \leq 50\%$	$0.3 < g_2 < 0.7$ (substitutable at low cost but with loss of performance)	$25\% \leq g_3 \leq 50\%$	$0.16 \leq g_4 \leq 0.28$	$1500 \leq g_5 \leq 2000$ (moderately concentrated)	$0 \leq g_6 \leq 1.0$	$69.6 \leq g_7 \leq 79$	$0.700 \leq g_8 \leq 0.800$
C_4 = Low risk	$g_1 > 50\%$	$g_2 \leq 0.3$ (easily substitutable at low cost, no loss of performance)	$g_3 < 25\%$	$g_4 < 0.16$	$g_5 < 1500$ (unconcentrated)	$g_6 > 1.0$	$g_7 > 79$	$g_8 > 0.800$
Criterion preference*	↑	↓	↓	↓	↓	↑	↑	↑
Lithium (Li)	1%	0.7	52%	0.144	4818	1.111	82.94	0.871
Aluminum (Al)	35%	0.7	0%	0.185	2327	0.072	71.84	0.777
Copper (Cu)	29%	0.7	9%	0.184	1332	0.407	75.17	0.788
Magnesium (Mg)	33%	0.7	<5%	0.221	8096	-0.391	66.37	0.736
Gold (Au)	30%	1.0	14%	0.154	621	0.051	72.20	0.742
Niobium (Nb)	22%	0.7	2%	0.179	8021	0.015	79.57	0.772
Nickel (Ni)	35%	0.7	2%	0.325	1458	0.068	69.32	0.700
Chromium (Cr)	19%	0.5	2%	0.144	2682	0.034	69.50	0.706
Beryllium (Be)	17%	1.0	11%	0.133	8491	1.111	82.76	0.896
Silicon (Si)	0%	0.7	0%	0.224	4846	-0.211	70.25	0.756
Iron (Fe)	40%	0.7	<1%	0.142	2112	0.253	74.61	0.788
Lead (Pb)	52%	0.7	10%	0.272	3097	0.003	71.19	0.762
Silver (Ag)	27%	1.0	71%	0.259	986	0.108	77.61	0.770
Rare Earth Elements (REEs)	<1%	0.7	100%	0.728	7595	-0.307	66.69	0.739
Titanium (Ti)	52%	0.7	0%	0.446	958	0.256	69.48	0.735
Zinc (Zn)	22%	0.7	10%	0.211	1758	0.109	71.97	0.765
Molybdenum (Mo)	33%	1.0	46%	0.337	2324	0.327	74.40	0.801
Platinum Group Metals (PGMs)	37%	1.0	35%	0.427	3387	-0.002	75.70	0.730
Vanadium (V)	0%	0.3	82%	0.355	3702	-0.364	70.91	0.733
Antimony (Sb)	18%	0.5	80%	0.270	6285	-0.380	67.69	0.734
Tantalum (Ta)	18%	0.7	28%	0.301	3167	-0.364	53.58	0.532
Tin (Sn)	22%	0.3	3%	0.296	2034	-0.271	59.74	0.616
Gallium (Ga)	37%	0.7	100%	0.213	6236	-0.233	68.19	0.754
Indium (In)	37%	1.0	100%	0.257	3374	0.259	70.88	0.805
Cobalt (Co)	32%	0.7	85%	0.358	2824	-0.548	67.46	0.638
Tellurium (Te)	0%	0.3	100%	0.501	4070	0.622	82.23	0.860
Graphite	0%	0.5	0%	0.203	4876	-0.373	63.41	0.695
Germanium (Ge)	42%	1.0	100%	0.214	4935	0.021	70.15	0.776
Tungsten (W)	46%	0.5	5%	0.180	6736	-0.327	68.02	0.730
Manganese (Mn)	37%	1.0	3%	0.506	1621	0.136	71.12	0.731
Boron (B)	0	1.0	0%	0.194	5097	0.034	70.55	0.774

Fig. 20 Supply risk matrix indicating the ranges of criteria values discerning between the allotment to each class and values for the selected sample materials (g_j = criterion; C_i = risk classes; *: the arrow 'up' signifies that the greater the value on the list of possible values, the better it is, and the arrow 'down' indicates the opposite

6.8. Supply risk profiles via SMAA-TRI and IRIS

The results of the risk class allocations of the raw materials are shown in Figure 21, illustrating the synergistic contribution of the SMAA-TRI and IRIS methods. The classes are colour-coded from left to right and ordered from the highest risk, C_1, to the lowest risk, C_4. This easily allows DMs to distinguish between the most and least critical materials. Each material is characterised with the share of classifications (CAI – Class Acceptability Indices) based on SMAA-TRI, which can range between 0% and 100% for each risk class (C_i). For different raw material and class combinations, these percentages indicate the proportion of the simulations (using randomly values for the weights and random values for the threshold λ) that place a given raw material in a given class. For each row in Figure 21, the overall sum of the CAI for the corresponding raw material's potential classifications is always 100%. For instance, the first row of Figure 21, indicates that REE is in class C_1 for approximately 75% of the simulations and in C_2 for approximately 25% of the simulations (the exact values are provided in the supplementary information, Excel sheets). CAI can be more concentrated on one C_i, such as in the case of Co and Cr, whose CAI are 99% C_2 and 85% C_3, respectively. In other cases, CAI can be more widespread among the classes. An example is Li, with 19% C_1, 55% C_2, 17% C_3 and 9% C_4. These differences in classifications are due to the combined effect of scoring of the raw materials on the eight criteria, their relation to the Pr_h and thresholds and the use of a range for λ. The more widespread the CAI are, the more the risk classification of the material depends on fixing the criteria weights and λ (subjectively, by a DM).

The SMAA-TRI results clearly show the distinction between those materials for which the classification is more robust than others, meaning that the uncertain modeling parameters (i.e. weights and λ value) have a lower effect on the variability of the sorting. Classifications that show more than 50% of the CAI for one class can be considered more robust than other classifications where this does not arise. This occurs for 26 out of 31 materials (i.e. REE, Te, In, Ge, B, Mn, Graphite, V, Li, Co, Si, Mg, Sb, Ta, Ag, Pb, Au, Ti, W, Fe, Sn, Ni, Cr, Cu, Al, Zn). Let us note that the models do not aim at advancing one single deterministic classification based on a single run of the input data. Rather, we consider a wide range of possible combinations of weights and preferences of the DM (through λ values between 0.65 and 0.85) for assignment to a certain class, leading to a probabilistic outcome. Consequently, the DM can clearly see some potential classifications which are more robust than other ones and make a more informed choice, knowing that the evaluation is robust according to multiple models settings.

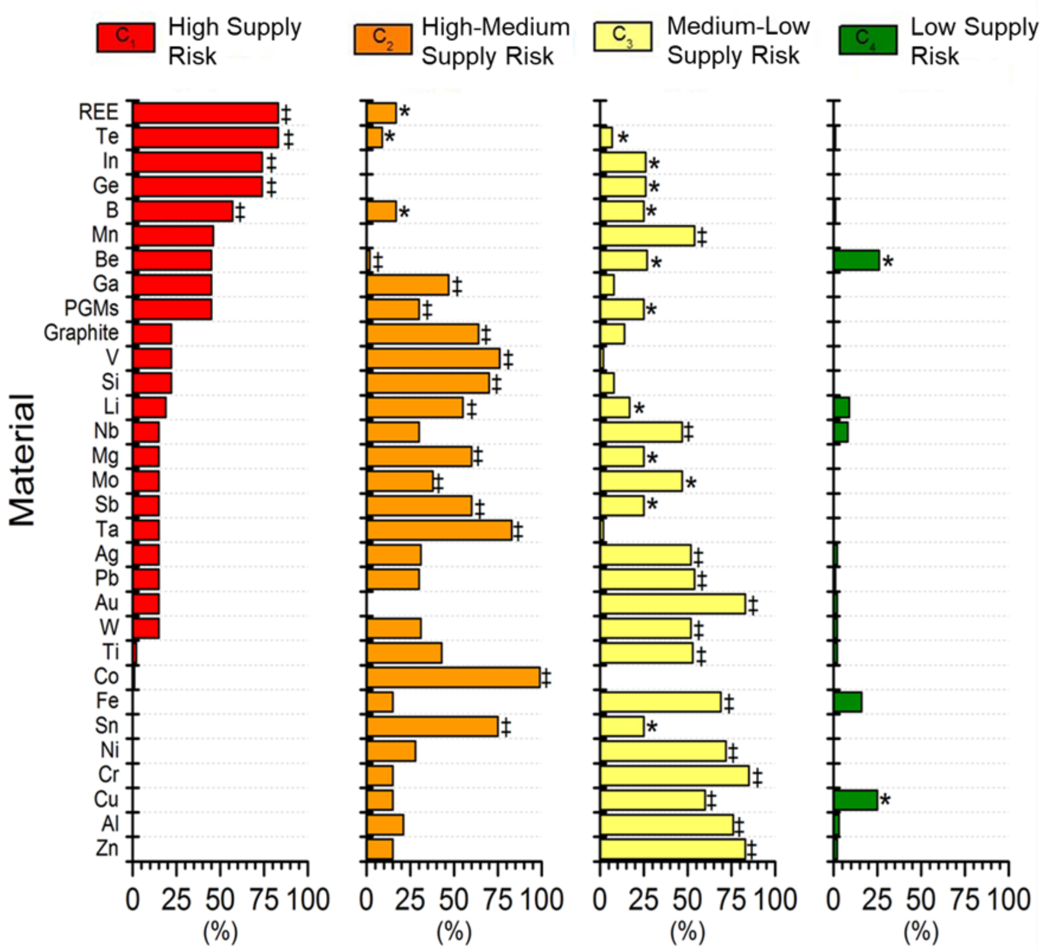

Fig. 21 Supply risk classification of thirty-one raw materials via SMAA-TRI (share of CAI % for each class) and IRIS (‡ = IRIS sorting with at least six criteria supporting the classification; * = IRIS sorting in cases where fewer than six criteria trigger the classification)

Furthermore, there are materials where the usefulness of a frequency-based visualisation of the results is even more apparent, and this occurs where a high percentage (e.g. $\geq$ 80%) of the Monte Carlo iterations support a certain class. In this regard, a nominal indication of a recommended class (e.g. possible classes are C_1 and C_2) can be misleading as a risk-averse DM might be inclined to select the worst from among the possible classes. However, when a high proportion of the CAI recommends a better class (e.g. 10% C_1 and 90% C_2), the DM may accept this sorting, understanding that the combined effect of the uncertain information can only in limited instances support the worst classification of the raw material. This is the case for Co (C_2 for 99% of CAI), Ta (C_2 for 83% of CAI), Au (C_3 for 83% of CAI), Cr (C_3 for 85% of CAI) and Zn (C_3 for 85% of CAI).

As presented in Section 6.6.3, Phase 2 of the decision aiding procedure refines the modelling. Firstly, information on the weights of the criteria can be introduced based on the work of the EU, leading to the constraint w_1, w_2, w_5, w_6 > w_3, w_4, w_7, w_8. In addition, it is possible to assume that DMs might accept three quarters of the criteria to be sufficient to justify a classification and would also like to know the actual weights assigned to the criteria. These modelling settings can be implemented with IRIS software and the results are shown in Figure 21 with the ‡ and * symbols. Symbol ‡ indicates the worst possible class if a DM accepts that a coalition of six criteria is sufficient to grant the classification (meaning that 75% of the criteria place the raw material in that class, or better). Symbol *, when present, indicates the cases where fewer than six criteria are able to trigger a better classification, while still respecting the constrain that w_1, w_2, w_5, w_6 > w_3, w_4, w_7, w_8.

For each raw material, different values for the criteria weights might lead to the same classification. For any given material-class pair that might occur, IRIS yields a representative combination of weights that leads to classify that raw material in that class. This combination is chosen, among other possible ones, by selecting the one that is farther away from violating any of the constraints. The specific weights that IRIS model calculates for each possible material classification are reported in the supplementary information, Excel sheets.

This setting leads to a more definitive differentiation of the materials because the available variability of the models parameters was restrained. It can be seen that the classification becomes more detailed: the number of possible recommended classes decrease between one and three when compared with the SMAA-TRI results. This step-wise approach can be used as a means to drive the decision-making process towards a more thought-through procedure.

For example, based on SMAA-TRI, there is a 15% and 30% chance of Nb being allocated to C_1 and C_2 respectively, a 47% chance of it being allocated to C_3 and only a 8% chance of it going to C_4. Hence, it can be assumed that there is a large probability of Nb being allocated to either class C_1, C_2 or C_3 if weights are missing (i.e. SMAA-TRI results). However, by imposing certain constraints on the results (i.e. weights and criteria coalition), C_3 is a class with at least 75% of the criteria in its favor (i.e. IRIS results), which could be considered sufficiently robust by a DM to perform an informed choice.

As far as the IRIS sorting are concerned, the high risk class (C_1) is assigned when there are less than six criteria supporting a better class, and their combined weight is (for some of the accepted weight vectors) insufficient to reach the λ. In cases where this happens (i.e. for REE, Te, In, Ge, B), then C_1 is recommended.

The high-medium risk class, C_2, is assigned when there are at least six criteria that support the classification. For example, C_2 is assigned for Be, PGMs and Li since there are at least six criteria that have a cumulative weight $\geq \lambda$ and that are at least as good as Pr_1. In some cases, there can be multiple potential classifications provided by IRIS where the weight vectors of the criteria are such that fewer than six criteria have enough combined weight to support the sorting and thus a lower risk classification is recommended, such as in the case of REE (C_2), Be (C_3 and C_4), PGMs (C_3) and Li (C_3) (raw materials with * in Figure 21).

Further considerations emerge with materials where there is an even spread of CAI involving up to all of the available classes, such as in the case of Li, Nb and Ti. This happens because (i) such materials have criteria that score in each class, (ii) a wide variability of weight vectors is accepted and (iii) λ ranges between 0.65 and 0.85. This modelling setting thus allows various combinations of weight vectors of the criteria that can (or not) have a sufficient cumulative weight to overcome λ in the SMAA-TRI simulations. It is especially in such cases that IRIS sorting can help with the interpretation of the results. Knowing that at least six criteria are in support of a certain classification and overcome λ enriches the decision-supporting potential, proposing at least C_2 for Li, C_3 for Nb and C_3 for Ti.

A potential issue of concern is what we defined as "class discontinuity", which is shown in the case of Au, which can be assigned to C_1 and C_3 but not C_2 or In, which can be assigned to C_1 and C_3 but non C_2. Other materials that suffer from this uncertainty are Ge and Mn. This phenomenon is due to the lack of criteria whose score is in the "jumped" class and thus support the assignment to it. In the case of Au for example, g_2 supports assignment to C_1. Under certain weight vectors g_2 receives such high weight (34% from IRIS software) that the remaining coalition of criteria cannot overcome the λ and consequently the highest risk level (C_1) is assigned (see also Figure 19). This means that in cases where the DM is willing to accept that g_2 has such high weight (thus high importance) then this is a plausible classification, otherwise only the better classes (i.e. C3) would be relevant to consider. ELECTRE-TRI is a non-compensatory method, hence if there are no criteria that support a certain class, then such class is never considered as a possible allotment, independently from the performance on the other criteria.

6.9. Minerals criticality matrix

The materials selected for analysis were Cu (medium-low supply risk), Al (medium-low supply risk), PGMs (high-medium supply risk) and REEs (high supply risk) with the consideration of the EU weights and criteria coalition constraints. The data used to estimate the economic importance of these materials for the automotive business, including revenue, cost of goods sold, gross profit and number of vehicles sold, were sourced from the JLR Annual Report 2014–2015 (JLR, 2015) and JLR’s Vehicle Sustainability Engineering Department.

The most likely substitute for Cu in automotive wiring and car electrical systems is Al (Yoshida and Doi, 2014). The advantage of using aluminium cables over copper counterparts is their low cost and lightweighting opportunities. Al has the potential to save up to 4 kg in the weight of a car and is approximately four times cheaper than Cu (Onstad et al., 2016). Hence, making a switch from Cu to Al for automotive wiring can help car manufacturers save money as opposed to generating additional cost. Al wire harness systems are already being supplied for use in Honda’s light vehicles and Toyota’s luxury vehicles, with the potential to make up about 30 per cent of the market in Japan by 2025 (Onstad et al., 2016).

Replacing Al with Mg in car manufacturing would allow a saving of approximately 28 per cent of vehicle weight (see Appendix 3 in **submission 5** for theoretical calculations of the lightweighting performance of different materials for the vehicle seatback frame in consideration of their density, tensile strength, component diameters and volume). However, these weight savings would come at a high cost. For example, the replacement of 407 kg of Al in a vehicle would require about 293 kg of Mg. The cost of this replacement per vehicle would be approximately £511 (cost of Al 407 kg * £1.48 = £602, the cost of Mg 293 * £3.80 = £1113). When this figure is multiplied by the 462,209 vehicles sold by JLR in 2015, the total cost of raw materials would increase by £236 million, or approximately 9 per cent of the company’s gross profit in 2015.

Despite their low content in a vehicle (less than 0.1% of total vehicle mass), PGMs are critical for the automotive sector because they are not substitutable in autocatalyst applications using current technologies (Tercero Espinoza et al., 2015). PGMs can replace each other in autocatalysts (e.g. palladium and ruthenium can replace platinum), but they are not substitutable with any other material. As long as vehicles with internal combustion engines remain dominant, any disruption to the PGM market has the potential to result in a severe economic impact on car manufacturers, with the most extreme scenario being a total loss of profit. Vehicles with internal combustion engines made up 100 per cent of JLR's sales in 2015.

REEs have a number of automotive applications, including in batteries, hybrid engines, metallurgy, ceramic capacitors and magnets (Chapman et al., 2013). Magnets account for approximately 30 per cent of the consumption of REEs and are used in every single vehicle (e.g. motors, hard disks and speakers). Replacing REEs in magnets is extremely difficult and advanced research activities in this field are ongoing. The list of possible substitutes includes nanocomposite materials, cerium, manganese (Mn) and gallium (Ga) compounds as well as cobalt- and samarium-based compounds (Tercero Espinoza et al., 2015). Among this list of substitutes, cerium and samarium are themselves REEs. Mn-Ga compounds show promising performance in high-technology applications in comparison to neodymium (Nd), the most widely used REE in magnets at present (Coey, 2014). However, while Mn is relatively cheap, the cost of Ga (£290/kg) is six times higher than that of Nd (£48/kg). Furthermore, Ga has also been classified as a critical material by the EU (EC, 2014) and as a material with high supply risk in this study (see Figure 21).

The cost of replacing Nd with Ga is approximately £73 per vehicle, on the assumption that the same amount of both materials would be needed (0.3 kg). Multiplied by the 462,209 vehicles sold by JLR in 2015, the total cost of raw materials would thus increase by £33.8 million, or approximately 1.3% of the company's gross profit in 2015. However, the quality of

Mn-Ga magnets is still incomparable to REEs, and the composition of a new, quality magnet material may take years, if not decades, to determine (Coey, 2014).

The economic importance of Cu, Al, PGMs and REEs was compared with the supply risk level of these materials in a materials criticality matrix (see Figure 22).

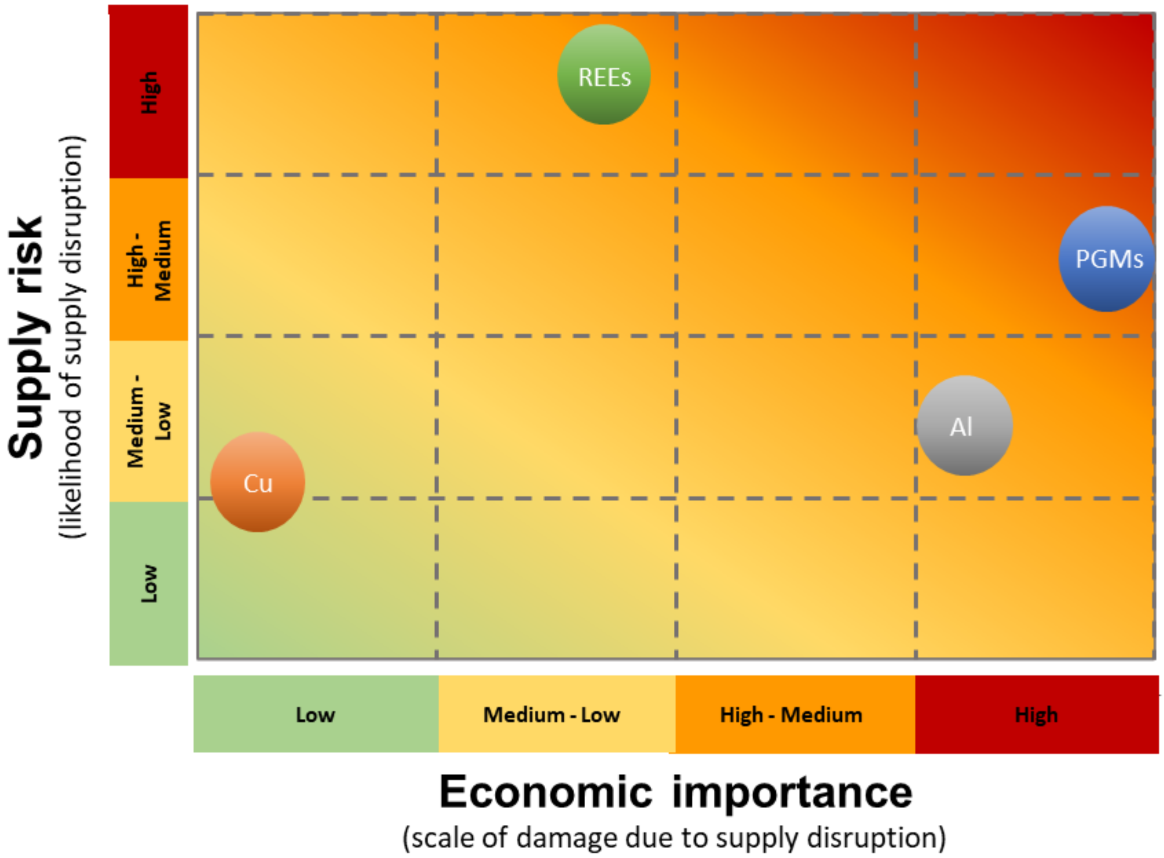

Fig. 22 Raw materials criticality matrix for JLR

The closer materials are to the upper-right corner of the criticality matrix (red-shaded area), the more critical they are from a business perspective. In this case, PGMs appear to the biggest concern for JLR as opposed to Cu, which is situated mostly in the green-shaded area. This study has avoiding classifying these materials as 'critical' or 'non-critical' as one may question the validity of such an arbitrary distinction (Nassar et al., 2012). Instead, the intention was to identify those metals that are more critical than others under certain conditions and constraints. This should immediately suggest that business policy or strategy should be explored for those materials that are of high criticality. This may involve developing product designs that do not include materials with a high supply risk, intensifying research into the development of a viable substitute material or investing in a mine rather than relying on the purchase of raw materials on the global market (Nassar et al., 2012).

6.10. Comparison of the results with the EC criticality study

Minerals criticality assessment exercises are system-specific, and hence not necessarily comparable with other studies (Glöser et al., 2015, Drielsma et al., 2016). For example, the latest EC criticality assessment (EC, 2017) relates to materials that are relevant to the European industry, while this study focuses on metals and metalloids used in automotive manufacturing; however, some comparison between both studies is possible.

The results obtained through a synergetic use of SMAA-TRI and IRIS are largely aligned with the EU's risk profiles of raw materials, with minor exceptions. For example, the supply risk of Te is considered by the EU as relatively low, while this study considers this material as high risk. This may be because the EU put a strong emphasis on substitutability, which largely drives their results (Chapman et al., 2013). Te is easily substitutable (risk class C_4); however, it performs low in other criteria (e.g. co-production and historical price volatility), not considered by the EU in their study. Hence, the weights allocated to the substitutability criterion, or the weights coalition with other criteria (such as environmental standards and subeconomic stability), were not enough to overcome λ and thus recommend the risk class profile better than C_1 (Te) and C_2 (V). This sorting could change if, for example, a higher weight would be assigned to substitutability than to other criteria, or λ would be lowered to 0.5.

The advantage of the combinatorial use of SMAA-TRI and IRIS is that it allows to investigate the possible changes in results by accounting for the uncertainty of input parameters, in this case the weights of assessment criteria. Other MCDA methods either use equal weighting or need specific weight values (not available in this study), while SMAA-TRI and IRIS can operate without or with limited information about the weights of input parameters (assessment criteria).

The economic importance of Al and REEs for the automotive sector does not deviate significantly from the economic importance of these metals for the EU economy (EC, 2017). For example, Al is a highly attractive material for a wide range of applications, including in low-carbon mobility, resource efficient packaging and energy efficient buildings. The intrinsic properties of Al, such as lightweight, barrier protection and endlessly recyclability, make it a perfect material for automotive, as well as other European industrial sectors, to make a substantial contribution in the battle against climate change and boost innovation across industrial value chains in Europe.

The economic importance of the REEs, both for the EU and automotive sector is medium-low, bearing in mind that there is no significant REEs transformation and manufacturing activity in the EU. A large proportion of EU consumption and imports of REEs to the EU comes from finished products (e.g. magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.). Furthermore, in most of their applications, REEs cannot be substituted without loss in performance. However, for economic reasons, many R&D strategies have focused on reducing the amount of REEs used in their different applications (EU, 2017).

Although still considered as critical materials by the EU (EC, 2017), the economic importance of PGMs in this study is higher than the one defined in the EU criticality study. This deviation is explained by the fact that PGMs are assessed individually in the EU study, as opposed to this study, where they were assessed as a group. As such, the economic importance of the PGM group in the EU study is based on the arithmetic average of the individual PGM results based on allocation of the end uses and the corresponding manufacturing sectors of each of the major end uses of the individual PGMs rather than the allocation of end uses for the overall PGM group to particular sectors (in this case automotive), which was the approach used in this study. EU is the highest consumer of platinum and an important consumer of palladium and rhodium for autocatalysts, but not necessary the highest consumer of ruthenium and iridium (Johnson Matthey, 2018).

Cu has a much greater economic importance in the EU criticality study than it has in this Innovation Report. This is because the Cu industry feeds into large value chains (e.g. building construction, infrastructure, transport, electronic equipment, etc.) that together represent a substantial part of the EU's industrial base. In this Innovation Report, the economic importance of copper for the automotive sector is relatively low due to the assumption that car makers can make a switch from Cu to Al for automotive wiring without much effort and with no or with a positive net value.

7. Implications of research outcomes

This section discusses the implications and limitations of the research outcomes that have resulted from this Engineering Doctorate research.

7.1. The readiness level of the A-SAM

A framework for the A-SAM consists of twenty-six midpoint impact categories and their 9 end-point counterparts. Twenty-one impact categories, representing environmental, resource and social performance, required the development of valuation models for the completion of A-SAM. Valuation models for twelve impact categories have been delivered to JLR over the period of this EngD project (ten through PwC and two through the work conducted for this EngD) (see Figure 23). Although models for resource depletion impact assessment have been primarily tested on metals and metalloids, they are also applicable to fossil mineral resources.

The A-SAM framework goes into great depth by providing a broad and comprehensive view about the sustainability performance of a car. The idea was to start from the most comprehensive understanding as possible, define gaps and weaknesses, and then develop novel capabilities to fill the identified gaps and weaknesses. This EngD sets guidance on what needs to be measured in an integrated and comprehensive sustainability assessment of vehicles and leaves the choice of what to include in the decision-making process to the discretion of individual companies. The system already provided to JLR focuses on twelve of the most common sustainability metrics for the automotive sector, for which scientific knowledge is more advanced. It serves as the basis for this system to expand as the understanding and knowledge develops.

Fig. 23 The level of readiness of the A-SAM at the end of this EngD project

Apart from time and resources, the level of complexity involved and the imperfection of existing measurement tools is an obstacle to delivery of a complete set of valuation coefficients for the A-SAM. LCA is capable of measuring all of the environmental and resource criteria proposed in the framework, although the method's reliability varies from one criterion to another. For example, impact assessment methods for human toxicity (such as the USEtox model) are less certain than, for instance, scientifically robust climate change impact assessment models (Hauschild et al., 2013).

Social impacts, such as human and labour rights and occupational health and safety, require complex systems of measurement because they may occur at each stage of the vehicle life cycle and especially in the supply chain (Traverso et al., 2013). GreenDelta has recently released an innovative and comprehensive database (see Ciroth and Eisfeldt, 2016) which can lay the foundations for this type of assessment in the future. This database contains global data for approximately 15,000 industry sectors and commodities and covers a broad set of quantitative and qualitative social indicators. The concept remains in its infancy and is therefore limited for conducting an accurate assessment. However, it is a significant step forward, which should allow for the analysis of hot spots along the entire supply chain.

Other social criteria such as vehicle noise, safety, interior air quality, congestion and mobility are largely customer-use impacts and are already monitored by OEMs' different business units. For instance, the NVH department measures noise and vibration performance, the Safety Attribute department measures vehicle safety performance, the Environment Attribute department monitors vehicle interior air quality, while engineers working on autonomous driving and traffic communication systems assess the potential impact of technology on traffic congestion. Hence, the development of valuation models and coefficients for these social impacts requires the support and commitment from different business units within JLR, not all of which were prepared to participate in this EngD project either due to the ethical reasons or simply due to the lack of interest in the FCA concept.

7.2. Implications of the results for business decision-making

There are two major ways in which the obtained results can support business decision-making: (1) optimising decisions by identifying win-wins and trade-offs between sustainability dimensions; and (2) providing information about the risk of price increases of minerals in the short- to mid-term scenarios.

7.2.1. Identifying win-wins and trade-offs

Although PwC is transparent about the valuation methods and tools they use (see Kering, 2013), the valuation coefficients developed by PwC were the intellectual property of the company, and hence could not be shared and used for the purpose of this EngD project. Nonetheless, the potential of FCA to support business decision-making is demonstrated based on the surplus cost estimates and the social cost of carbon available in the literature.

In this EngD, the surplus cost estimates represent the external cost of PGMs and lithium extraction imposed on future generations (from now up to 2070) in the form of increased extraction costs resulting from a decrease in highly concentrated and easily accessible resources (Vieira et al., 2016). However, for the mining industry, policymakers and scientists, climate change is currently of far greater concern than resource depletion (Ponsioen et al., 2014). Through a comparison of the social cost of carbon with the SCP indicator, one can tell the relevance of resource scarcity in relation to climate change impacts.

The International Platinum Group Metals Association (IPA) has recently conducted an LCA study to assess the environmental impacts of the primary and secondary production of

PGMs as well as the benefits of using PGMs in catalytic converters (IPA, 2013). They estimated the global warming potential (GWP) for platinum, palladium and rhodium from primary production, fabrication, use phase and secondary production to be 33, 25 and 30 kg CO_2-eq per gram of material, respectively.

Tol (2012) estimated the mean of the social cost of carbon based on a meta-analysis of 232 estimates published in the literature. The mean social cost of carbon is 49 euro/tonne of CO_2, which, once converted to USD per kilogram and adjusted for inflation, is USD 0.0536 per kilogram of CO_2. An average PGMs loading per LDV is 5.38 grams (see Table 8), which, when multiplied by the GWP for each mineral and USD 0.0536, gives an external cost of CO_2 emissions per vehicle of USD 9.5 for platinum, USD 7.2 for palladium and USD 8.7 for rhodium. Figure 24 compares these estimates with the surplus cost indicator.

As is evident in Figure 24, the social cost of depleting PGMs far exceeds the social cost of climate change. Hence, the scarcity of PGMs should be of greater concern to decision makers than the CO_2 emissions associated with the production and use of these minerals. Furthermore, the total external cost (GWP and SCP) is lowest in the case of palladium and greatest for rhodium. When compared with the market price of these metals in 2014 (USD 1389 per t oz for platinum, USD 810 per t oz for palladium and USD 1172 per t oz for rhodium), palladium seems to be the optimum material for use in catalytic converters from an economic, environmental and social point of view due to its lowest market price and external costs (GWP and SCP costs).

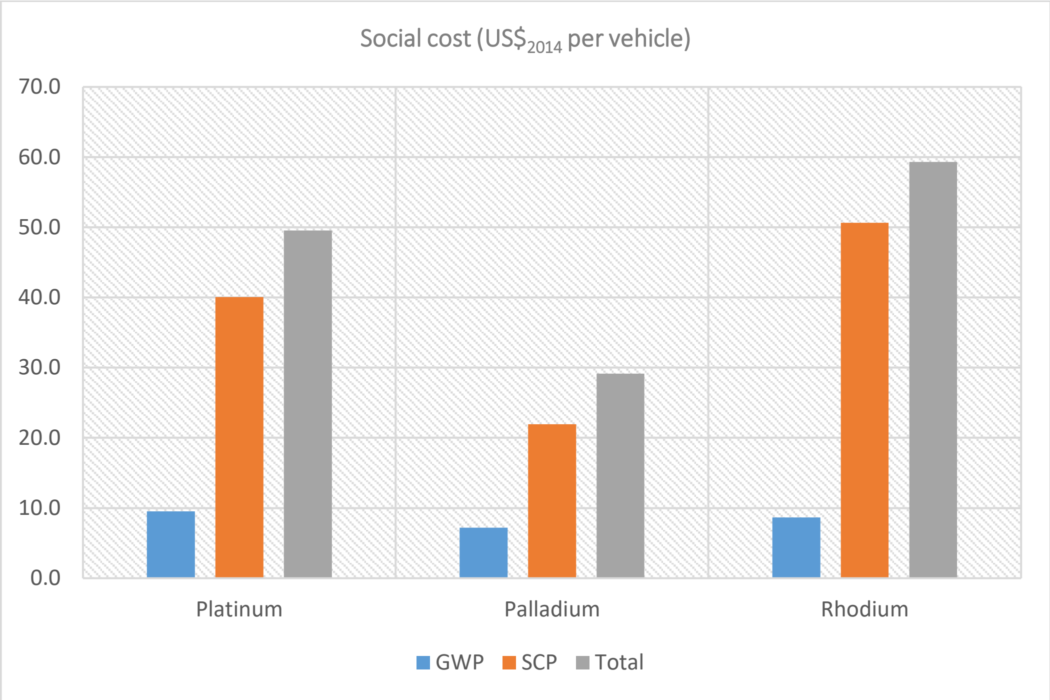

Fig. 24 A comparison of the social cost of climate change and resource depletion for platinum, palladium and ruthenium

7.2.2. Identifying the risks of minerals price increases and supply disruption

The surplus cost estimates provide a mid- to long-term outlook for the real threat of resource scarcity and the potential economic implications of their depletion. For example, the comparison of surplus cost estimates for PGMs and lithium with the current production costs (see Table 11), indicates that problematic price increases of lithium are unlikely if the latest technological trends in the automotive sector will continue up to 2070. Surplus costs for PGMs are approximately one-third of the current production costs in all production scenarios; hence, a threat of their price increases by 2070 will largely depend on the discovery of new deposits and the ability of new technologies to push these costs down over time. This also applies to lithium if the increasing electrification of road transport will continue up to 2070.

Cost-cumulative availability curves, on which a surplus cost indicator is based, constructed for PGMs and lithium reflect the availability of minerals only from known deposits under current conditions (this is, current technology, prevailing labour and other input prices, and so on). Ideally, these curves should concern all known and unknown deposits as well as their current and future production costs (Yaksic and Tilton, 2009). This, however, is rarely the case in practice as reliable information on unknown deposits and future technological developments is not available.

According to Yaksic and Tilton (2009), this does not pose a serious problem as long as one keeps in mind that both new discoveries and the cost-reducing effect of new technology are likely to shift these curves down and to the right over time. It is likely that new blocks will be continuously added to cost-cumulative availability curves for PGMs and lithium between now and 2070 as geological knowledge and extraction technology improves. This, in turn, will have an impact on surplus cost estimates for these metals, which currently do not incorporate any information about technological change over time and entry of new high-quality mines to the market. It is expected that new discoveries and technologies will shift surplus costs down in the future. Hence, the results provided in this EngD can be interpreted as the upper cost limits (the worst-case possibilities), which are likely to be decreasing with the discovery of new deposits and cost-reducing technologies. The surplus cost estimates can be easily updated if new data become available in the future.

The surplus cost estimates provide a mid- to long-term outlook for the real threat of resource scarcity and the potential economic implications of their depletion. Raw materials criticality assessment identifies minerals with a high eventuality of supply disruption, and thus increasing commodity prices in the short term (10 to 20 years).

The criticality assessment proved that even though a particular mineral may play only a minor role in car manufacturing, the potential implications of a disruption to its supply could be severe. For example, the robustness analysis, structured upon the combined use of MCDA outranking methods, determined that the PGMs have either a very high or high eventuality of supply chain disruption. As there are currently no substitutes to replace PGMs in autocatalysts, disruption to the supply of PGMs may have catastrophic consequences for automotive companies, with the most extreme scenario being a potential loss of all revenue and profit. This should immediately suggest that business policy or strategy should be explored for PGMs, for example, in the form of intensifying research into the development of a viable substitute material.

Conversely, copper, next to aluminium and iron, is the major contributor to the total weight of the vehicle. The risk of supply disruption for copper is largely medium or low and it can be replaced at low cost in car wiring by aluminium. Hence, the criticality of copper is much lower than of PGMs and no urgent actions and business policy securing the supply of this mineral are needed.

7.3. Limitations of the results

Surplus cost - considering the fact that cost-cumulative availability curves for PGMs and lithium (and resultant surplus cost estimates for these metals) capture only a small part of the total available resources and utilise the current production costs data, the results should not be interpreted as an indication of availability and potential scarcity of these resources in the long-run. Tilton and Lagos (2007) and Humphreys (2013) explained that the long-run mineral costs and prices are far more reliable warning indicators of future resource scarcity or lack of availability.

This, however, is both a limitation and a strength of this work. Modelling these costs and prices in the long-run may suffer from huge uncertainties and significant inconsistencies by trying to anticipate something that nobody can know (Humphreys, 2013). These uncertainties were avoided in this study by providing a mid-term outlook for the real threat of PGMs and lithium scarcity and the potential economic implications of their depletion from now up to 2070. Drielsma et al. (2016) recommended that existing cost-cumulative availability curves are the most suitable to analyse individual minerals in the 30-100-year time frame.

Minerals criticality assessment - the economic impact assessment analysis is limited in the sense that it is exclusively focused on the market price of a material and its potential substitute while other costs, such as idle labour and equipment capacity, inventory carrying, new machinery and tools, delays, new designing and research and development (Norrman and Jansson, 2004, Shu et al., 2014), are not considered. It was impossible to conduct this type of high-level analysis in this study due to the lack of data and resources. JLR will perform a more detailed analysis internally once the concept is validated and the most vulnerable materials have been identified.

Even though the supply risk methodology has been applied to thirty-one materials, the criticality assessment considered only four of these. This EngD has supplied JLR with the internal capabilities and tools required to conduct a more detailed analysis of all thirty-one materials and also additional ones. The economic impact assessment of minerals supply disruption is system-specific and should be straightforward to perform by JLR internally.

8. Conclusions

This Engineering Doctorate (EngD) project, with the support of the consulting company PricewaterhouseCoopers, has developed and proved with real world data an innovative model that will enable large car manufacturers to evaluate options, identify win-wins and optimise trade-off, while making complex and multi-disciplinary sustainable decisions. The Automotive Sustainability Assessment Model (A-SAM) measures and quantifies a broad range of economic, environmental, resource and social impacts caused by the automotive sector. By adapting a rigorous and robust approach, it translates these impacts into their monetary equivalents, which is a language and thinking that could be understood in different business areas and by different stakeholders. It enables managers and design engineers in the automotive sector to develop a better understanding of the environmental, resource and social impacts of their activities, products, processes and materials used, while still ensuring cost-effectiveness when making decisions. It can expose new business or investment opportunities for automotive organisations, in line with the principles of sustainable development, by making them more transparent and visible for decision-makers.

This section summarises the main achievements of this EngD project with respect to research objectives defined in Section 1, discusses research impacts and outcomes from this project and provides recommendations for future work.

8.1. Research achievements

Objective 1: To identify FCA methods that have been developed to date and select the most appropriate method for the automotive setting.

Achievements:

- A systematic and rigorous literature review of 4381 papers extracted ten important FCA methods and these were: the Sustainability Assessment Model (SAM), Forum For the Future's sustainability accounting, monetised Life Cycle Assessment, Sustainability Value concept, Environmental Profit and Loss Account, extended Life Cycle Cost analysis, Centre for Waste Reduction Technologies, Ontario Hydro, ExternE and US Environmental Protection Agency's method.
- The SAM has been identified as a well-developed and potentially practical tool for application in an automotive setting due to its ability to measure and translate a broad range of economic, environmental, resource and social effects into a monetary unit score, something which is currently lacking within the automotive industry.

Objective 2: To adapt the FCA method for the automotive industry by developing a comprehensive set of assessment criteria for automotive sustainability assessment.

Achievements:

- A comprehensive automotive sustainability assessment framework, which was still lacking within the automotive industry, has been developed by selecting a set of assessment criteria from the literature and refining these through an interview study with experts from the automotive sector.
- The developed framework consists of 26 midpoint impact categories and 9 potential end-point effects of the selected criteria, including: climate change, ecosystem quality, impact on biodiversity, resource depletion, human health, quality of life and macroeconomic indicators such as gross value added, dividends and taxes.

Objective 3: To develop a valuation model for environmental and social risks and impacts.

Achievements:

- A comprehensive and innovative approach to resource depletion impact assessment has been proposed by developing two complementary models for capturing the economic consequences of resource depletion: (1) the surplus cost model measuring the net present value of the increase in mineral production costs in the mid- to long-term associated with each additional extraction of a mineral commodity, (2) the raw materials criticality assessment model measuring the risk of minerals supply disruption and the economic impact of their disruption on the business in the short-term.
- Valuation of another ten criteria, global warming potential, photochemical ozone creation potential, acidification potential, particulate matter formation, eutrophication potential, water consumption, land use, mobility capability, employment (quantity) and occupational health and safety, has been carried out by PricewaterhouseCooper to complement this EngD project

Objective 4: To test the developed model based on 'real world' input data

Achievements:

- The surplus costs model has been tested based on Platinum Group Metals and lithium suggesting that problematic price increases of lithium are unlikely if the latest technological trends in the automotive sector will continue up to 2070. Surplus costs for PGMs are approximately one-third of the current production costs in all production scenarios; hence, a threat of their price increases by 2070 will largely depend on the discovery of new deposits and the ability of new technologies to push these costs down over time.
- The supply risks analysis was conducted for thirty-one metals and metalloids used in car manufacturing. The analysis revealed that rare earth elements and tellurium have a very high eventuality of supply chain disruption, closely followed by indium,

germanium and boron. Conversely, the results suggest that the risk of supply disruption for iron, copper, zinc and aluminium is mostly medium or low.

- The criticality assessment for four minerals determined that the PGMs are of potential concern for automotive organisations. PGMs have either a very high or high eventuality of supply chain disruption. As there are currently no substitutes to replace PGMs in autocatalysts, disruption to the supply of PGMs may have catastrophic consequences for automotive companies, with the most extreme scenario being a potential loss of all revenue and profit.

8.2. Research impact

This EngD project resulted with the publication of the following conference and journal papers:

- Jasinski D. Meredith J. & Kirwan K. (2015). Full Cost Accounting in the Automotive Industry: A Systematic Review and Methodology Proposal. In: *Sustainable Automotive Technologies: Proceedings of the 6th ICSAT, 29th September – 1st October 2014 Gothenburg, Sweden, pp. 127-136,* Springer International Publishing.
- Jasinski D. Meredith J. & Kirwan K. (2015). A Comprehensive Review of Full Cost Accounting Methods and their Applicability to the Automotive Industry. *Journal of Cleaner Production, Volume 108 Part A, pp. 1123-1139.* This paper builds upon the conference paper and it provides helpful clues for researchers interested in exploring FCA in the future by reviewing, analysing and synthesising the broad range of relevant sources from diverse fields in this topic area.
- Jasinski D. Meredith J. & Kirwan K. (2016). A Comprehensive Framework for Automotive Sustainability Assessment. *Journal of Cleaner Production, Volume 135, pp. 1034-1044.* This expert-driven framework has been developed in the FCA context,

but it can serve as a design structure for a wide range of sustainability assessment methods and tools (e.g. multi-criteria decision analysis). It provides guidance on what needs to be measured in an integrated sustainability assessment of vehicles and leaves the choice of what to include in the decision-making process to the discretion of individual companies.

At the time of writing, the following two articles are under review for high-impact scientific journals:

- Jasinski D. Meredith J. & Kirwan K. The life cycle impact for platinum group metals and lithium to 2070 via surplus cost potential. *The International Journal of Life Cycle Assessment*, submitted in October 2016, status at the time: minor revision. This paper demonstrate how surplus cost potential estimates for metals can be calculated without the utilisation of ore grade function and by collecting primary economic and geological data with the level of quality comparable to expert-driven consulting services.
- Jasinski D. Cinelli M. Dias L. Meredith J. & Kirwan K. Assessing Supply Risks for Non-Fossil Mineral Resources via Multi-Criteria Decision Analysis. *Environmental Science & Technology*, submitted in March 2017, status at the time: under review. This article proposes a novel approach to raw materials criticality assessment upon the synergic combination of MCDA methods. This is the first study of its kind to propose a classification system for raw materials criticality based on a synergistic use of outranking methods, or based on driving robust conclusions from a set of weighting vectors.

8.3. Recommendations for future work

a) **Surplus cost potential model** – surplus cost estimates for PGMs and lithium are based on cost-cumulative availability curves, which at the moment capture only a small part of the total available resources (only known deposits) and utilise the current production costs data. Modelling and incorporating unknown deposits and potential future mineral production costs into these curves could be the subject of future work. However, one needs to bear in mind that modelling these variables in the long-run may suffer from huge uncertainties and significant inconsistencies by trying to anticipate something that nobody can know much. Also, surplus cost estimates were delivered only for six metals: platinum, palladium, rhodium, ruthenium, iridium and lithium. The future work may involve estimating surplus costs for the whole range of minerals (including fossils).

b) **Raw materials criticality** – even though the methodology for supply risk assessment has been applied to thirty-one materials, it is also applicable to additional ones. Furthermore, more assessment criteria could be incorporated in the future (e.g. Policy Potential Index or global supply concentration at the company level), once they will comply with data quality and availability.

c) **The automotive SAM** – the set of assessment criteria developed for the automotive SAM provides a broad picture of the sustainability performance of a vehicle. Valuation models for twelve impact categories have been delivered to JLR during the time of this Engineering Doctorate (ten through PwC and two through the work conducted for this EngD). If JLR wishes to drive improvements in sustainability within its operations through an understanding of its total sustainability impact, then a complete set of valuation indicators would need to be developed. The company will have to allocate more time and resource to evolve the A-SAM concept and develop a complete FCA solution for the automotive sector

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